Draft Report

Protocol for 100 Years Service Life of Corrugated High Density Polyethylene Pipes

PART II - Stress Crack Resistance, Oxidation Resistance and Viscoelastic Properties of Finished Corrugated Pipes

Prepared for the

Florida Department of Transportation

by

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August 12, 2003

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ABSTRACT

The Florida Department of Transportation (FDOT) retained Simpson Gumpertz & Heger Inc and Drexel University to develop testing and analysis protocols that can assess pipe properties and design procedures to ensure 100-year service life of HDPE corrugated pipes. This report presents the results of Drexel University study on long term properties of the pipes. Four long-term properties were evaluated in this part of the study, and they were stress crack resistance (SCR), oxidation resistance, tensile strength and flexural modulus. The focus of the evaluation was on the finished pipe properties so that effects of the manufacturing processes and pipe designs were included.

For SCR properties, the effects of manufacturing processing were observed in pipe liner tests. Also, pipe junctions and vent holes were found to be susceptible to stress cracking, but the sensitivity varied with pipe designs. In predicting 100 years crack free pipes, Popelar shift factors were found to yield acceptable master curve at a site temperature of 20°C. Two test methods (FM 5-572 and FM 5-573) were developed to describe the SCR tests and to predict 100 years crack free performance.

The oxidation resistance of the corrugated pipes was evaluated based on both antioxidants depletion and degradation of polyethylene. The antioxidant content and depletion rate in the pipe were assessed using oxidative induction time (OIT) value coupling with water or air incubation. The lifetime of the antioxidants and corrugated pipes was assessed using Arrhenius equation by utilizing elevated temperatures to accelerate the reactions. The method to describe the step-by-step test procedure to predict lifetime of antioxidants and corrugated pipes was developed as FM5-574.

The long-term design parameters, tensile strength and flexural modulus, are predicted using Popelar shift factors. A tensile creep rupture test was utilized to determine the 100-year tensile strength of the corrugated pipe, while a stress relaxation test on the finished pipe was used for the 100-year flexural modulus. Three new test methods, FM5-575, FM5-576 and FM5-577, were developed to describe the test procedures for determining 100-year tensile strength and modulus.

The interim and full specifications were also developed to be implemented at different time periods for HDPE corrugated pipes.

1.0 INTRODUCTION

This is Part II of the report on the study entitled “Test Protocol for 100 Year Service Life of Corrugated High Density Polyethylene (HDPE) Pipes”. Part I of the report addresses the structural analyses and design procedures that are suitable for corrugated HDPE pipes. Part II of the report focuses on the material properties and time-dependent behavior of the pipe. The report consists of three parts: stress crack resistance of HDPE corrugated pipe, antioxidants in pipe to ensure oxidation stabilization and long term tensile and flexural modulus properties.

A series of laboratory tests were performed to assess the various issues in the three study areas of the project to establish specification requirements for 100-year crack free service life of HDPE corrugated pipes for potential use on Florida DOT projects. However, the intention of these laboratory tests is to verify the test methods that are incorporated in this test protocol, as well as to illustrate the test procedures and analyses. Due to the limited number of pipe samples being evaluated in this project, the test data may not represent the behavior of all HDPE corrugated pipes. In addition, some of the tests require a much longer testing time than the duration of this project, the preliminary predicted values presented in this report do not reflect the long-term performance of the pipes.

2.0 TEST MATERIALS

A 24-inch diameter HDPE corrugated pipe was supplied by each of two manufacturers for the laboratory study. These pipes are coded as P-1 and P-2. Table 1 shows the properties of the two pipes according to some of the methods listed in AASHTO M 294. The tests were performed on the compression plaques that were prepared by remolding the cut pipe pieces instead of HDPE resins which are not available for the evaluation. Thus, material properties in Table 1 cannot be directly compared with those required in M 294 which refers to opaque non-carbon black resin material. Also the oxidative induction time (OIT) test was included to characterize the antioxidant amount in the pipes.

Table 1 – Properties of P-1 and P-2 pipes

Properties	P-1	P-2
Density (g/cc)	0.953[(1)]	0.951[(1)]
Melt Index (g/10min)	0.16	0.25
Flexural modulus (psi)	124400	117700
Tensile Strength (psi)	4040	3700
UV stabilizer (%) (minimum)	2.6	2.6
NCLS* test (hours)	17.8	19.8
OIT+ test (minute)	26.4	30.6

* NCLS test – Notched constant ligament stress test
\+ OIT test – Oxidative induction time test
(1) The density values were obtained by calculation using equation in ASTM D 3350.

3.0 LABORATORY TESTS TO EVALUATE CRACK FREE SERVICE LIFE OF HDPE CORRUGATED PIPES

3.1 Introduction

The material specification for HDPE corrugated pipes used in transportation applications is based on AASHTO M294 “Standard Specification for Corrugated Polyethylene Pipes”. In the year 2002, the specification adopted the NCLS test which is now ASTM F2136 “Standard Test Method for Notched Constant Ligament Stress (NCLS) Test to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe”. The modification enhances the SCR of HDPE resins used for corrugated pipes. The NCLS test is a constant stress test in which stress relaxation does not developed, thereby presenting a greater challenge to SCR of the test specimens in comparison to constant strain test (i.e., ASTM 1693) which was required by the specification until 1999. The minimum cell classes defined in AASHTO M294 are shown in Table 2 together with the specified property ranges within each of the cell classes.

In the current M294 specification, environmental stress crack resistance (ESCR) and hydrostatic design basis (HDB) tests, are not specified; instead the NCLS test was added into the specification. The conditions of the NCLS test are defined to be at 50°C in 10% Igepal® solution under an applied stress of 600 psi. The average failure time of five test specimens must be greater than 24 hours and no single specimen failure shall be less than 17 hours.

Table 2 – Cell Class Properties for HDPE Corrugated Pipes

Properties	Cell Class	Value
Density	3	< 0.945 – 0.955 g/cc
Melt Index	3	< 0.4 – 0.15 g/10 min
Flexural modulus	5	110,000 to <160,000 psi
Tensile Strength	4	3,000 - <3,500 psi
ESCR*	0	unspecified
HDB+	0	unspecified
UV stabilizer	C	2% minimum carbon black

* ESCR – Environmental stress crack resistance

\+ HDB – Hydrostatic design basis.

However, the M-294 specification retained the 90° pipe bending test for the evaluation of SCR of the finished pipes. This bending test is based on the same stress condition as ASTM D1693, by testing the pipe section under a constant strain condition, thereby allowing stress relaxation to take place during the testing. This finished pipe test does not appropriately challenge SCR properties of the pipe, and the test is impractical for large diameter pipes. More importantly, the test does not challenge the locations that are sensitive to stress cracking, such as junctions, longitudinal profiles and processing defects. Alternative SCR tests on the finished pipe were developed in this study and are incorporated into this test protocol for crack free service life prediction. The new SCR tests are applied to both short and long-term evaluations. The short-term evaluation refers to tests that are used for quality assurance and quality control (QA/QC) purposes to confirm the properties of pipes that have previously demonstrated 100-year crack free performance by manufacturers or users. On the other hand, the long-term evaluation employed tests that are performed under a range of different environmental conditions for long-term prediction purpose.

3.2 Stress Crack Resistance of Corrugated Pipes

In the current M294, the NCLS test focuses only on the pipe resin; thus, the effects of the extrusion process are not evaluated. Since corrugated pipes have a complex geometry profile, some parts of the pipe may be susceptible to stress cracking due to high stress concentrations. This protocol utilizes three SCR tests to evaluate different parts of the corrugated pipe. The test specimens are taken directly from the pipe so that the process and design effects can be assessed.

3.2.1. Stress Crack Resistance of the Corrugated Pipe Liner

In the NCHRP Report 429-Table 6, it is shown that the majority of field cracked pipes exhibited circumferential cracking that took place at the liner near the junction between liner and corrugation of the pipe, as shown in Figure 1. Moore (1995) utilized three-dimensional finite element analysis to examine the stress distribution in corrugated pipe under different burial conditions and found that an axial tension existed in the liner near the junction region. Therefore, the pipe liner is a critical component regarding crack free service life evaluation.

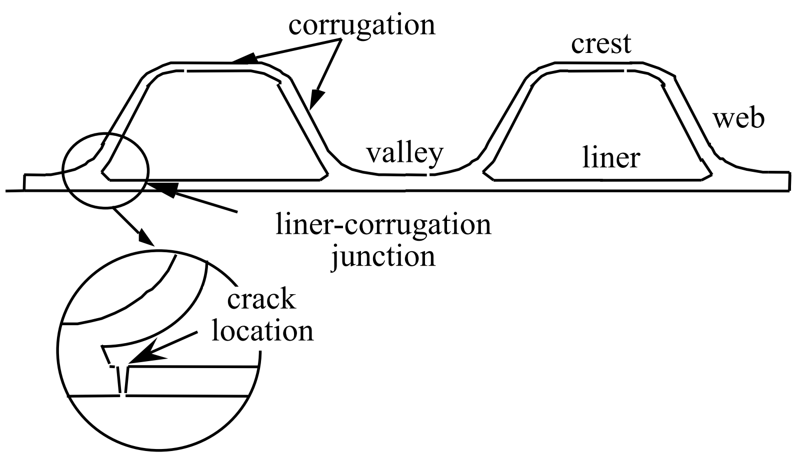

Figure 1 – Schematic diagram illustrating the location of circumferential cracking in HDPE corrugated pipes.

The test method used to evaluate the pipe liner is described in the Florida Method of Test FM 5-572 – Procedure A (The test method is included as Appendix A of the report). Table 3 shows the summary of results for the two pipes that were used to verify the method. (The individual test data are included as Appendix G of the report.)

Table 3 – Results of NCLS test of pipes P-1 and P-2

Pipe	Average Failure Time of Molded Plaque (hr)	Average Failure Time of Pipe Liner (longitudinal) (hr)
P-1	17.8	12.6
P-2	19.8	19.5

The test data in Table 3 show that one of the pipe liners exhibits noticeably different SCR properties compared to the corresponding compression molded material. Such difference is caused by the manufacturing process effects which exist in the pipe liner but not the plaque.

In addition, the ductile-to-brittle curves of each of the pipe liners were established, as shown in Figure 2. The slopes of the ductile and brittle curves of both pipes are very similar and they are approximately 0.10 and 0.55, respectively. However, the slopes of the brittle curves are steeper than those reported in the NCHRP Report 429 in which the brittle slopes obtained from compression molded plaques were found in the range of 0.24 to 0.44. The steep brittle slope resulting from the pipe liner again indicates the effects of the extrusion process which decreases the SCR of the pipe.

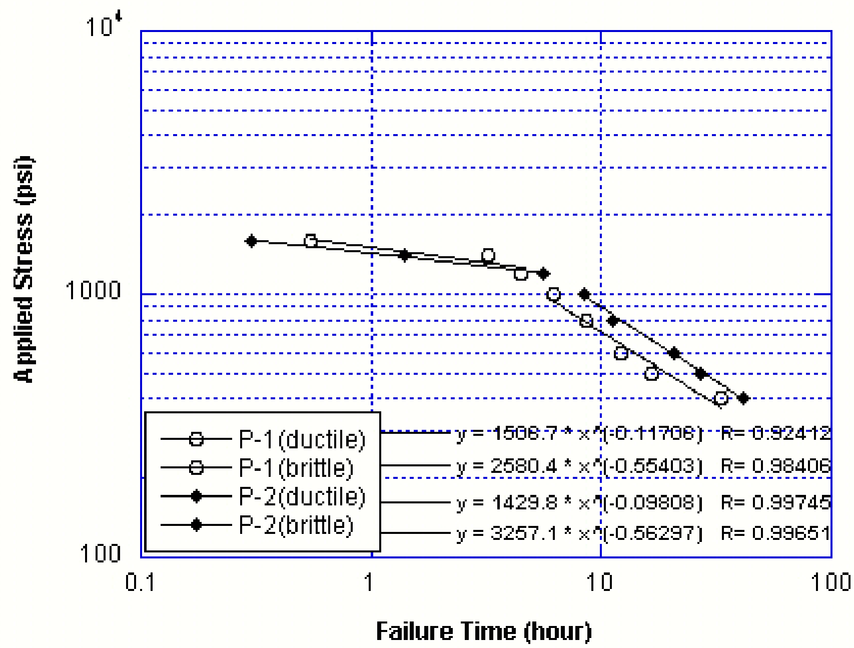

Figure 2 – Ductile-Brittle curves of two tested pipes, P-1 and P-2

3.2.2 Stress Crack Resistance of the Liner/Corrugated Junction

As shown in Figure 1, the junction between the liner and corrugation is susceptible to stress cracking due to abrupt changes in the pipe geometry. The junction geometry is governed by the pipe design as well as the extrusion process. If an axial tensile stress is imposed across the junction, as indicated by Moore (1996), cracking will take place.

A new SCR test was developed based on the preliminarily work that was reported in NCHRP Report 429. The test procedure to evaluate the liner/corrugation junction is described in the Florida Method of Test FM 5-572 – Procedure B. The ASTM D 638 Type IV die size was adopted in this test. Depending on the width of the valley, two sides of the junction can be evaluated either simultaneously or separately. Table 4 shows results of two pipes that were used to verify the test method.

Table 4 – Results of the junction test on pipes P-1 and P-2

Pipe	Failure Time (hr)	Comments
P-1 (both sides)	207.2 1238	Two out of five specimens failed. Failure occurs at the inner liner first and then growth through the material. (Three specimens are still on-going after 1500 hr.)
P-2 Side one	62	All seven specimens were failed with standard deviation value of ±28 hr.
P-2 Side two	882 1120 1030	Three out of four specimens failed. (One specimen is still on-going after 1500 hr.)

The data in Table 4 clearly indicate the vulnerability of the junction or adjacent areas towards stress cracking. For the P-1 pipe, the failure of the junction-specimen was not at the junction. The cracking actually started from the inner liner and then through the valley part of the pipe, as shown in Figure 3.

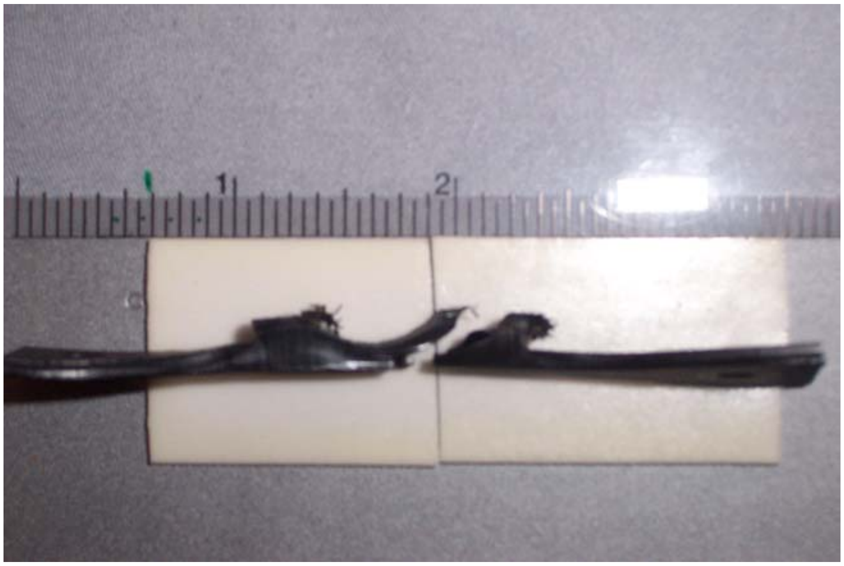

Figure 3 – Failure of the junction-specimen from pipe P-1.

In P-2, the geometry of the junction definitely governed failure. One side of the junction exhibited much greater crack resistance than the other. The failure took place at the junction between liner and corrugation, as shown in Figure 4.

Figure 4 – Failure of junction-specimen from pipe P-2

3.2.3 Stress Crack Resistance of Longitudinal Profiles

The NCHRP Report 429-Table 6 shows that in some of the field cases, longitudinal cracking was observed in the corrugated pipe. Some of the longitudinal cracks were noted to be along the vent hole or mold line of the annular profile pipes. Vent hole and molded line cracking was observed in Site J of the Report 429 (noted that the vent hole photos were not included in the report.) Furthermore, one of the PIs of this project has extensive experience in field performance of the corrugated pipes, and he has observed vent hole cracking in the field. Thus, these locations shall be evaluated to ensure long-term crack free performance of the pipe.

A new SCR test was developed. The test procedure to evaluate the longitudinal profiles is described in Florida Method of Test FM 5-572 – Procedure C. The ASTM D 638 Type IV die size was adopted in this test. The specific profile that is tested is positioned at the center of the constant neck section of the specimen. In this laboratory study, the selected longitudinal profile was a vent hole to illustrate and verify the test method. Table 5 shows the test results which indicate that cracking at longitudinal profiles (in this case, the vent holes) is possible. Of significance is that the failure resulting from this test appeared very similar to those observed in the field. Figure 5 shows the failed specimen. Cracking started from the inner liner and then progressed through the crown of the vent hole.

Table 5 – Results of the longitudinal profile

Longitudinal Profile	Failure Time (hr)	Comments
Vent hole	176 783.6 855.7	Three out of five specimens failed. Failure started from the inner liner and then the crown. The other two specimens are still on-going after 1200 hr.

Note: this set of tests was performed under applied stress of 500 psi due to equipment limitations. The actual test should be performed at 600 psi

Figure 5 – Failed longitudinal profile (vent hole) specimen

However, the test data in Table 5 were resulted from applied loads that were calculated based on the valley thickness of the pipe. In addition, the bending stress that was induced due to straightening of the specimen was not removed from the applied load. Since test specimens were taken from the circumferential direction of the pipe, they consist of a curvature that varies with the diameter of the pipe. The smaller pipe diameter creates a greater curvature in the test specimen. Under a constant tensile test configuration, the curved test specimen was forced to be straightened; thus, induced tensile stress on the liner part of the vent hole. Without considering this induced tensile stress, the liner portion of the specimen was subjected to a stress higher than the test intended.   In the newly developed Florida test method, the induced stress due to the straightening of the test specimen was subtracted from the applied load. Also the thickness of the liner was used to calculate the applied load instead of the valley thickness.

Since the failure started at the liner of the vent hole, the upper part of the vent hole is removed or cut, so that the applied load is transmitted through the liner only.

3.3 Methodology to Predict a 100-year Crack Free Pipes

The three tests described in Section 3.2 are designed for QA/QC purposes. The test environment is intended to accelerate failure mechanisms so that tests can be completed in a relatively short period of time. The test results do not directly reflect the long-term performance of the pipe unless a correlation is established over a period of time. However, the QA/QC tests are critical in validating all pipe productions requiring the 100-year crack free standard.

Regarding the 100-year crack free performance of the corrugated pipes, since there are no long-term performance case histories available for pipes that are made from the newly adopted resins, accelerated laboratory tests shall be used for the prediction. The conditions of the acceleration tests shall be as close to the field situation as possible. In the field, the liner of the drainage pipes is exposed to two media: water and air. Therefore, these two environments shall be used in the tests for predicting the long-term performance.

3.3.1 Prediction Method

The 100-year crack free pipe prediction was achieved using the temperature accelerated method. A set of NCLS tests was performed on the pipe liner in either water or air under different stresses at three elevated temperatures. The test data were then shifted to the site specific temperature (assumed to be 20°C) using the two constants defined by Popelar, et al. (1990), as shown in Equations (1) and (2). The master curve at 20°C will be used to determine the crack resistance property of the pipe.

$$a_T = \exp\left[-0.109\left(T - T_R\right)\right] \quad (1)$$

$$b_T = \exp\left[0.0116\left(T - T_R\right)\right] \quad (2)$$

where:

a_T = *horizontal shift function (time function)*
b_T = *vertical shift function (stress function)*
T = *temperature of the test*
T_R = *target temperature*

3.3.2 Water Environment

The NCLS tests were performed on the liner part of P-1 and P-2 pipes. The applied stress ranged from 300 to 1000 psi at temperatures of 40, 50 and 60°C. Note that due to the large number of tests; only two specimens were tested at each stress level. Figures 6 and 7 show the stress versus failure time plots at three temperatures for P-1 and P-2, respectively. The slopes of the curves at these three temperatures are relatively similar to each other for both pipes, indicating that the failure mechanism at all three temperatures is similar.

The three sets of data are shifted using equations (1) and (2) to form a master curve. The shifted data are shown in Figures 8 and 9 for P-1 and P-2, respectively. For both pipes, the 60^{o}C are slightly out of alignment with the other two temperatures. However, the shifted data are acceptable. The equation of the master curve in Figures 8 and 9 can be used for crack free lifetime prediction. For P-1, the stress and failure time relationship can be expressed by Equation (3). Using this equation, the pipe can be crack free for 100 years if the axial tensile stress is below 45 psi at an average site temperature of 20^{o}C under water environment.

$$\sigma = 14227 * t^{-0.426} \tag{3}$$

Similarly, Equation (4) is applied to P-2. Using this equation, the pipe can be crack free for 100 years if the axial tensile stress is below 50 psi at an average site temperature of 20^{o}C under water environment.

$$\sigma = 18872 * t^{-0.437} \tag{4}$$

3.3.3 Air Environment

A series of NCLS tests were performed on the liner part of the P-1 pipe at three different elevated temperatures using a forced air oven. The applied stresses ranged from 200 to 600 psi at temperatures of 50, 60 and 70^{o}C. Note that due to the large number of tests; only one specimen was tested at each stress level. Figure 10 shows the stress versus failure time plot at three temperatures. The slopes of the curves at three different temperatures are almost parallel to each other, confirming that the failure mechanism was very similar.

The three sets of data are shifted using equations (1) and (2). The shifted data are shown in Figure 11. Similar to the water data, the 60^{o}C are slightly out of alignment with the other two. However, the shifted data are acceptable. The equation of the master curve in Figure 11 can be used for crack free lifetime prediction for pipe P-1. The stress and failure time relationship can be expressed by Equation (5). Using this equation, the pipe can be crack free for 100 year if the axial tensile stress is below 170 psi at an average site temperature of 20^{o}C under air environment.

$$\sigma = 7748 * t^{-0.28} \tag{5}$$

By comparing test data obtained from water and air environments, the failure time is significantly longer in air than in water. In the NCHRP Report 429, the results of the field investigation indicate that the circumferential cracking took place in both wet and dry regions (i.e., invert and crown regions) of the pipe. Based on those field observations and the application function of the pipes, testing in a water environment seems to be an appropriate approach in predicting the crack free service life.

Recognize that the NCLS test uses a notched specimen. The purpose of the notch is to shorten the time for crack to form by creating a high stress concentration at the tip of the notch, thereby generating a consistent failure time under the same test parameters. Although the probability for pipes to have defects with similar stress concentration as the notch is largely unknown, the pipe does contain many stress concentration locations, such as junction between liner and corrugation, different types of longitudinal profiles, processing induced defects, and construction damages.

A Florida Method of Test FM 5-573 is developed to describe the step-by-step procedure using data obtained from laboratory accelerated tests to predict SCR behavior of the pipe at site temperature. The test method is included as Appendix B of this report.

3.3.4 Correlation between Different Test Environments

In the three incubation media, Igepal®, water and air, the 10% Igepal® solution yields the greatest acceleration of all, as can be seen in Figure 12. The slopes of the brittle curves in 10% Igepal® and water are very similar, suggesting that test specimens failed under a similar mechanism. The test liquid (10% Igepal® or water) probably penetrated to the notch tip and enhanced the formation of craze which leaded to cracking. The 10% Igepal® solution can shorten the failure time by a factor of 0.58 in comparison to water. Using this factor, the crack free lifetime prediction in water based on the junction test (i.e., the new SCR test – Procedure B) can be estimated by assuming that the slope of the brittle curve from the NCLS test on pipe liner remains unchanged (In order to predicting the lifetime using junction specimens, the slope of the brittle curve must be properly established.) The estimation procedure is described in the text that follows.

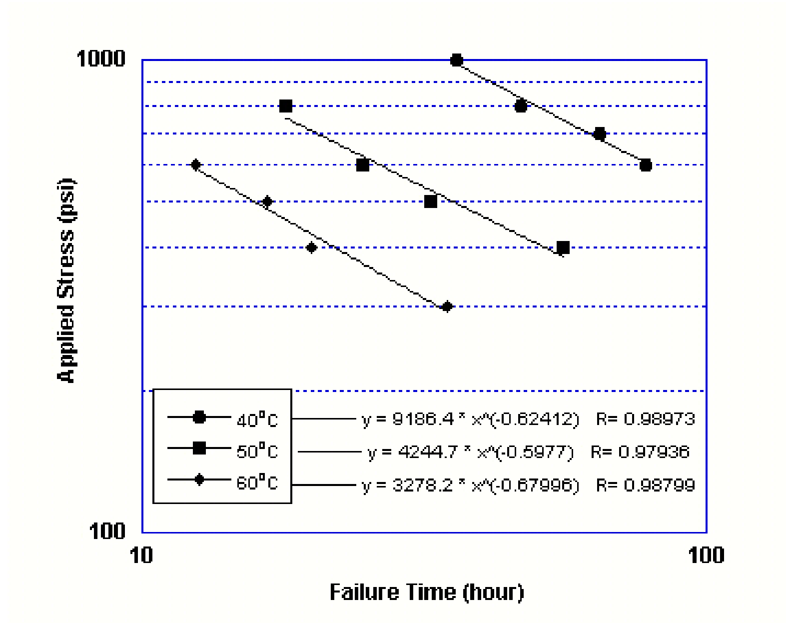

Figure 6 – Applied stress versus failure time curves of P-1 in water

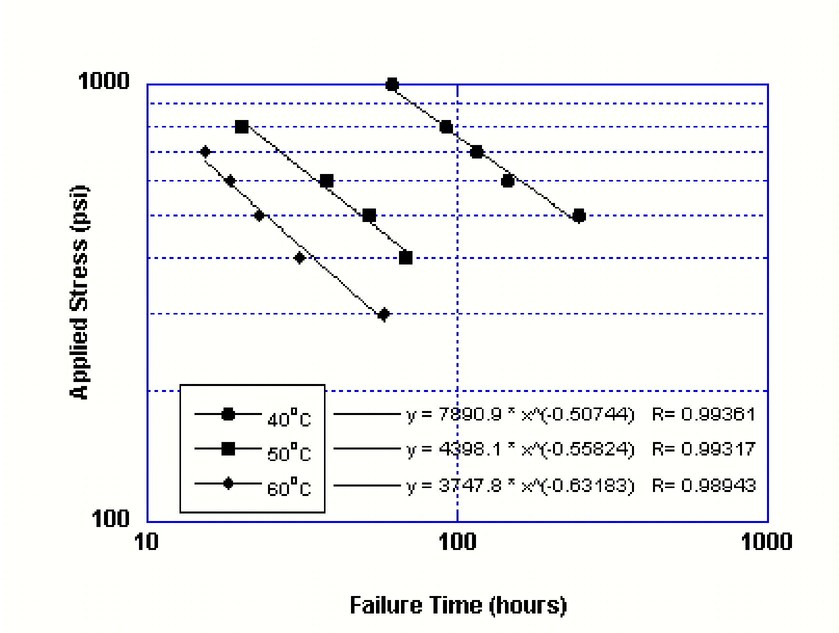

Figure 7 – Applied stress versus failure time curves of P-2 in water

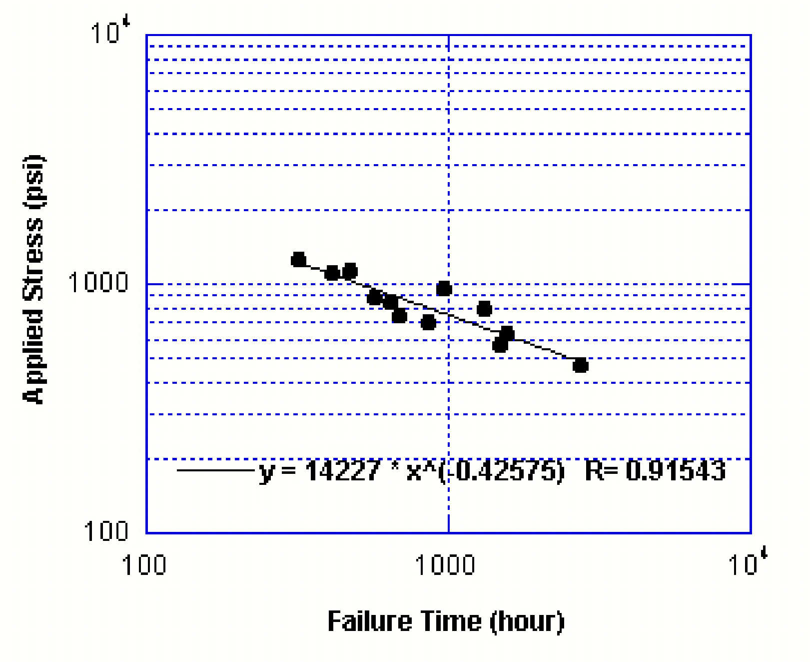

Figure 8 – Shifted data for P-1in water environment

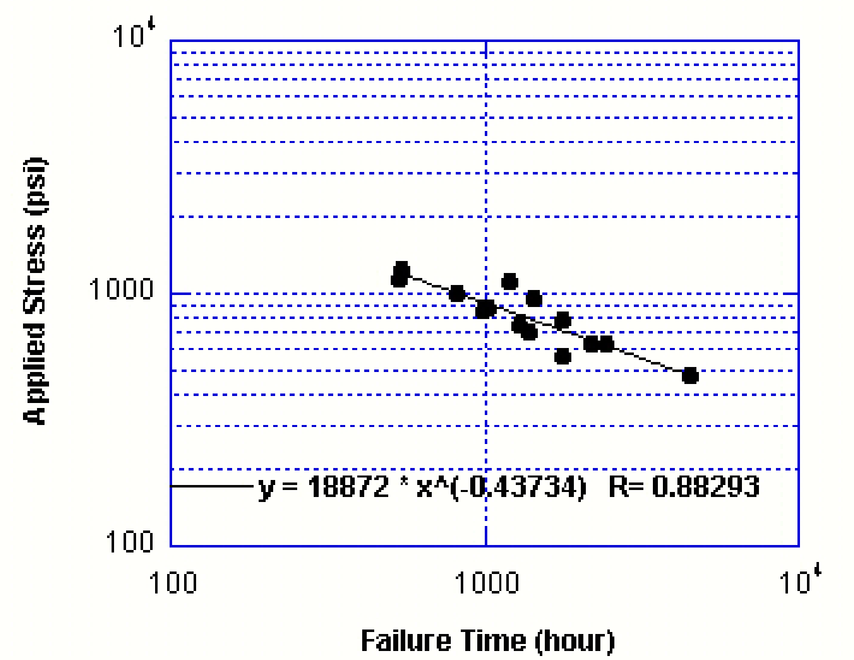

Figure 9 – Shifted data for P-2 in water environment

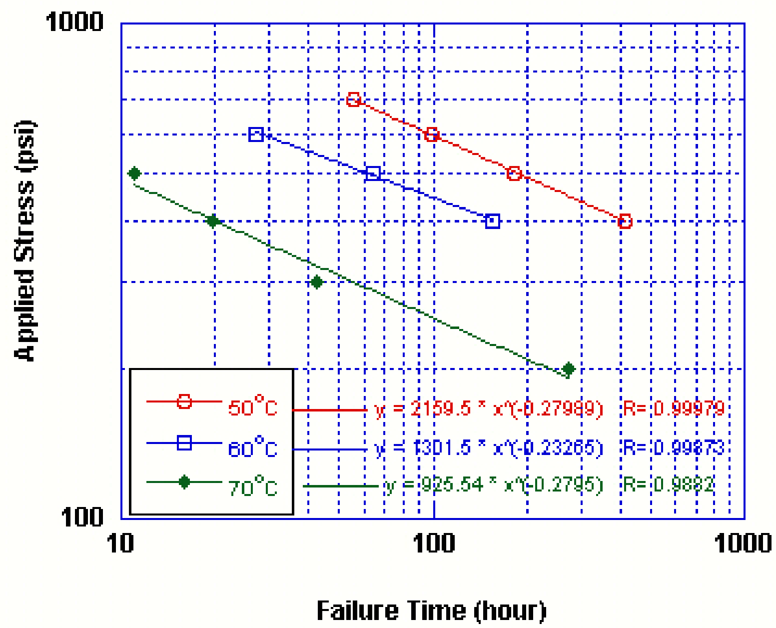

Figure 10 – Stress versus failure time plot for three different temperatures in air

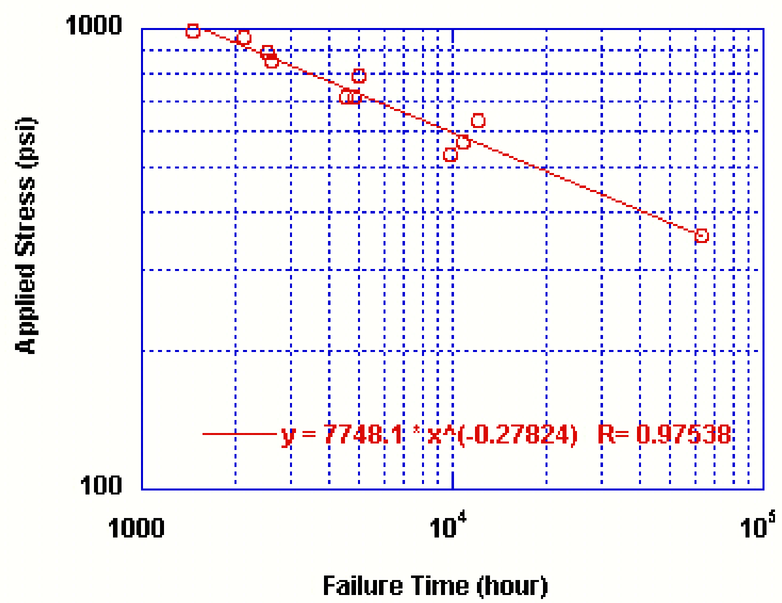

Figure 11 – Shifted air data for pipe P-1 in air environment

Result of the junction test in 10% Igepal® at 50°C σ *= 600 psi, t = 62 hr*

Result of the junction test in water at 50°C: σ *= 600 psi, t = 62/0.58 = 107hr*

Shift data to 20oC use Equations (1) and (2): σ *= 852 psi, t = 2816hr*

Equation (4) for P-1 NCLS test in water: $\sigma = 14227 * t^{-0.426}$

Substitute results of junction test to Equation (4) to obtain the constant:

$$852 = A\,(2816)^{-0.426}$$

$$A = 25092$$

Equation for junction test in water: $\sigma = 25092 * t^{-0.437}$

Allowable axial tensile stress for 100-year crack free pipe:

$$\sigma = 25092 * (876000)^{-0.437}$$

$$\sigma = 64 \text{ psi}$$

In contrast, the slope of the brittle curve in air is much shallower than in Igepal® and water. The cracking is purely caused by the applied stress; there was no environmental factor effect (i.e., water or Igepal®). Due to the difference in the slopes, it is not appropriate to correlate the failure time between air and Igepal®.

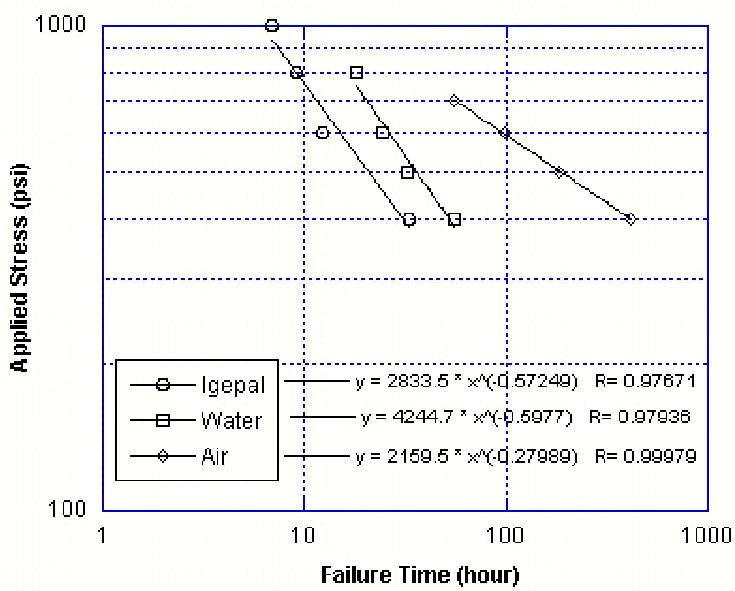

Figure 12 – Stress versus failure time curves in three test environments at 50°C testing temperature.

3.4 Summary of Laboratory SCR Evaluation

The SCR behavior of two HDPE corrugated pipes was evaluated. The evaluation focused on three specific locations of the pipe which are the inner liner, liner/corrugation junction and longitudinal profile. A QA/QC test (FM 5-572) was developed to assess the susceptibility of the stress crack at these three locations.

In order to investigate the effect of the test media, NCLS tests were performed in three different test environments; 10% Igepal®, water and air. The data confirm that the 10% Igepal® solution provides the greatest acceleration to the crack growth rate. Furthermore, the failure mechanisms are found to be very similar in between 10% Igepal® and water; but they are significantly different than that in air.

In predicting a 100-year crack free pipe, NCLS tests were performed at three different elevated temperatures in environments of water and air. The resulting data were then shifted to 20°C using the Popelar's constants. In the air environment, it was found that the maximum allowable axial tensile stress in the pipe was determined to be 170 psi to ensure 100-year crack free service life; however, the maximum allowable tensile stress decreased to 50 psi in the water environment for the two pipes used in the laboratory evaluation. The FM 5-573 was developed to describe the prediction procedures.

4.0 LABORATORY TESTS TO EVALUATE ANTIOXIDANTS IN HDPE CORRUGATED PIPES

4.1 Introduction

As shown in Table 1, the current AASHTO M294 does not require the evaluation of antioxidants in the HDPE corrugated pipe except the cell class defined in ASTM D 3350. In the NCHRP Report 429, a large variation was found in the antioxidants of 14 evaluated commercially new pipes, as shown in Figure 13. The amount of antioxidants in the pipe is expressed by the OIT value which ranges from few minutes to over 40 minutes.

The function of antioxidants in the corrugated pipe is to protect the polyethylene from oxidation degradation. The mechanical properties (including SCR) can only be preserved by properly formulated antioxidants. Thus, the lifetime of antioxidants plays an essential role in the overall service life of the pipe.

The overall oxidation mechanisms can be divided into three conceptual stages, as shown in Figure 14 (Hsuan and Koerner, 1999).

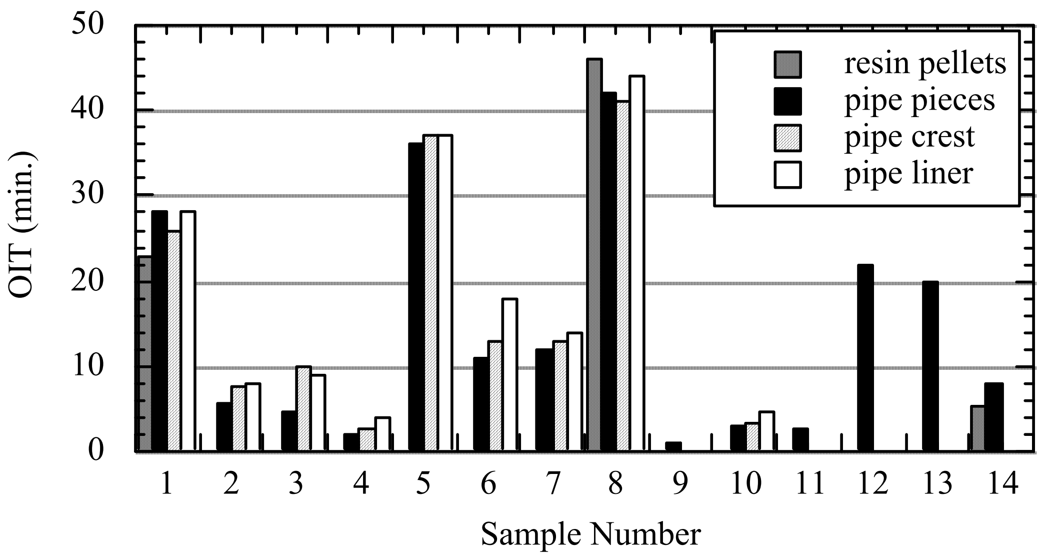

Figure 13 - OIT data of fourteen commercially new pipe samples

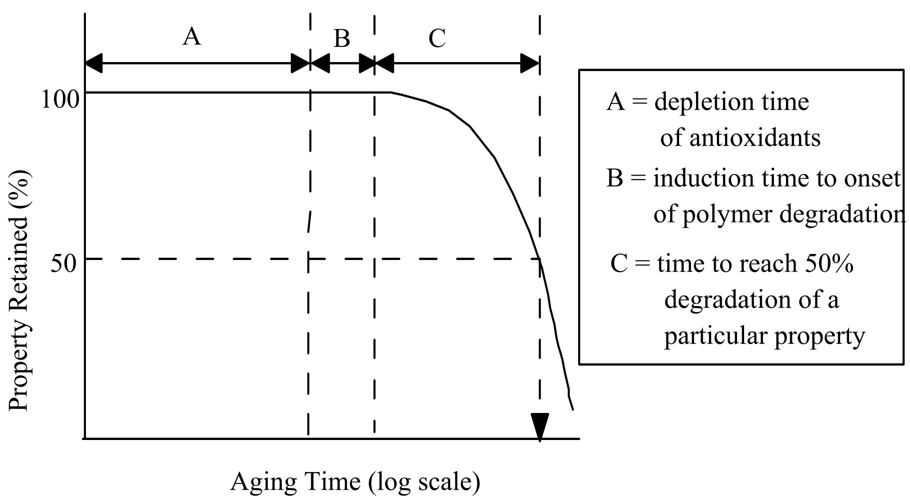

Figure 14 – The three conceptual oxidation stages of HDPE

- Stage A represents time to consume all of the antioxidants in the pipe. The duration of this stage depends on the type and amount of antioxidants, the site ambient environments or simulated laboratory testing conditions.
- Stage B is the induction time which is the inherent property of the unstabilized polymer. In this stage the polymer reacts with oxygen and generates free radicals

and hydroperoxide (ROOH), as expressed in Equations (6) and (7). The duration of this stage is governed by the concentration of hydroperoxide.

$$RH \xrightarrow{Energy} R\cdot + H\cdot \tag{6}$$

$$R\cdot + O_2 \rightarrow ROOH + R\cdot \tag{7}$$

- Stage C is the autocatalytic stage of the oxidation in which the formation of free radicals accelerates due to decomposition of ROOH, as indicated in Equations (8) to (10). The onset of the Stage C is when the hydroperoxide in the polymer increases to a critical concentration. The series of free radical reactions that take place in Stage C result in breaking polymer chains which leads to the degradation in mechanical properties of the materials.

$$ROOH \xrightarrow{Energy} RO\cdot + OH\cdot \tag{8}$$

$$RO\cdot + RH \rightarrow ROH + R\cdot \tag{9}$$

$$OH\cdot + RH \rightarrow H_2O + R\cdot \tag{10}$$

Note: In Equations (6) to (10), *RH* represents the polymer chain and compounds with (·) are free radicals.

Gedde's group has published a series of papers on the oxidation of hot water pressure pipes. Their findings were summarized in a review paper (Gedde, et al., 1994). In their study, the long-term performance of pressurized pipe was evaluated using method similar to ASTM D2837. The test pipes were subjected to a series of internal pressures using either air or water, and was incubated in either water and/or air environment at temperatures ranging from 60 to 105^{o}C. The failure modes of the pipe are illustrated in Figure 15. At Stage I, pipes fail by ductile mode. At Stage II, pips fail in brittle mode via stress crack growth. At Stage III, the effect of mechanical loading becomes insignificant due to extremely low applied stresses so that the pipes fail in brittle mode by oxidation degradation of the polymer. The transition between Stages II and III may sometimes be difficult to define. Karlsson, et al. (1992) found that the formation of carbonyl groups which resulted from the oxidation degradation of polyethylene took place much earlier than the onset of Stage III. However, due to the low applied stress, it took a longer time for the pipe to fail than at a high applied stress.

By correlating Figures 14 and 15, the onset of the Stage III is within the Stage C, while the exact position would be dependent on the applied stress. Nevertheless, the onset of the Stage III must be well beyond the design life of the application. Gedde's data show that a gas pipe with appropriate antioxidants and good stress crack resistance properties, the onset of Stage III can be predicted to 1000 years at 20^{o}C in water/air environment; however, without antioxidants, the onset of Stage III shortens to 11 years (Viebke, et al, 1994). Janson (1995) also extrapolated the onset of Stage III using test data that were presented by Gaube's group (Gaube, et al, 1985) and reach 500 years at 20^{o}C; however, types of antioxidants in the tested pipes were not presented.

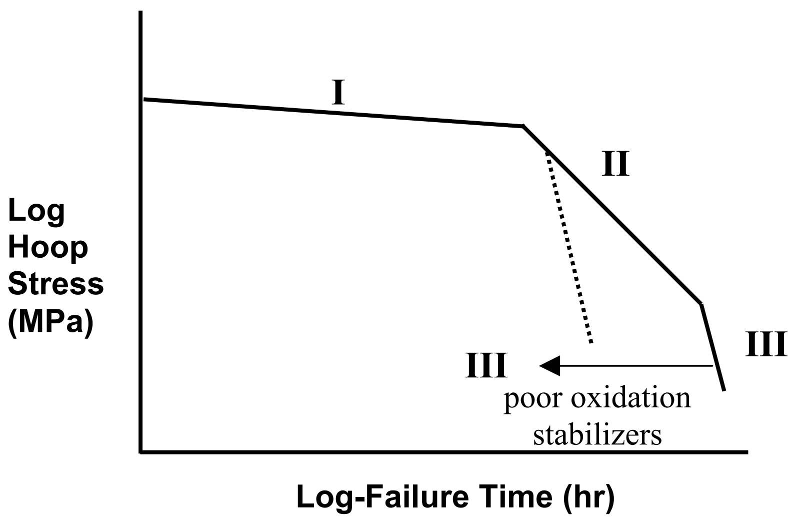

Figure 15 – Schematic drawing to illustrate the three failure stages in pressure test of smooth wall pipes.

The published data on pressurized pipes clearly demonstrate the importance of the antioxidant package in long-term performance of HDPE pipes. However, there are many types of antioxidants from which different formulations can be generated to target performance requirements. Each antioxidant formulation performs differently under air or water environment and it must be evaluated accordingly. Figure 16 shows the antioxidant depletion with time of five different geomembranes with unknown antioxidant formulations. The data indicate that Geomembrane E contains very different antioxidant than the other four (Hsuan and Guan, 1998).

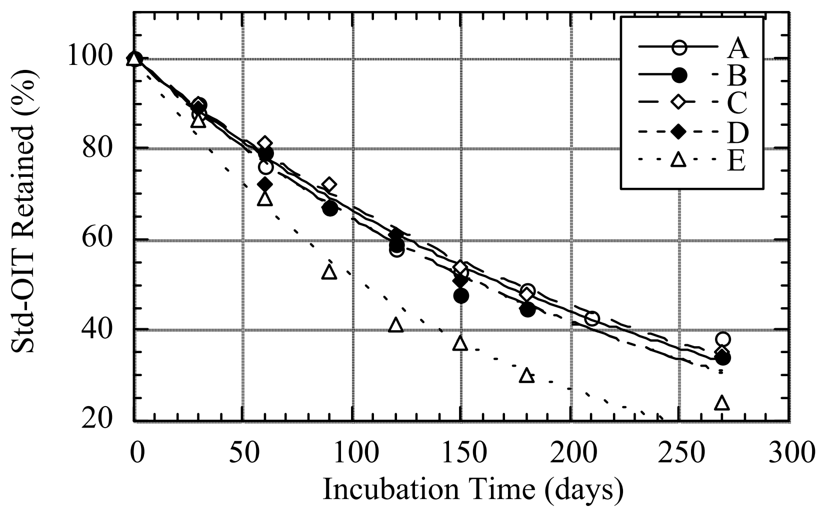

Figure 16 – Depletion of antioxidants with time for five HDPE geomembranes with unknown antioxidant formulations

The pressurized pipe test is an ideal performance test that challenges the antioxidant properties and SCR simultaneously. However, it requires long testing times (in the order of years) to yield sufficient data for analysis. Alternatively, short term accelerated tests have been developed to verify the oxidation resistance of the material (Hsuan and Koerner, 1999). The approach of the short term accelerated tests is to evaluate antioxidant and stress cracking separately.

4.2 Method to Evaluate Antioxidants

For assessing antioxidant content in the corrugated pipe, two tests are available and they are oxidative induction temperature (IT) and oxidation induction time (OIT). A brief description of each of the tests is presented below:

- IT – the test is a dynamic test by heating the test specimen under air at a heat rate of 10°C/min until oxidation of polymer takes place. The outline of the test procedure is described in ASTM D 3350, but there is no separate ASTM standard written on this method. In the ASTM D 3350, a 220°C IT value is specified to ensure sufficient antioxidant in the resin. However, the implication of the specified value in regard to the long-term oxidation resistance of the pipe is not stated.

- OIT – the test procedure is described in ASTM D3895. The test measures the duration for the polymer to oxidize at a constant temperature of 200°C under oxygen atmosphere. The test is well-established as one of the analytical tools to evaluate the amount of antioxidants in the polymer. The test has been used to investigate the antioxidant package in the hot water pressure pipes (Karlsson, et al, 1992, Smith, et al, 1992 and Veibke and Gedde, 1998) as well as to assess and predict the lifetime of antioxidants in the HDPE geomembranes (Hsuan and Koerner (1999) and Sangam and Rowe (2002)).

The correlation between IT and OIT was recently investigated on four different grades of polyethylene by Schmid and Affolter (2002). They found that the IT exhibited a significantly lower standard deviation in both repeatability and reproducibility than OIT. However, the sensitivity of the IT decreases significantly with rising temperature, as shown in Figure 17. Similar correlation was also observed by Karlsson, et al, 1992, as shown in Figure 18. Also note that the specified IT value of 220°C in ASTM D3350 corresponds to approximately 10 minutes or less OIT based on these two graphs.

The IT seems to be suitable test for QA/QC of antioxidants in the pipe due to its low standard deviation. However, the sensitivity of the test decreases significantly when IT value exceeds approximately 230°C which corresponds to OIT value between 10 and 20 minutes. Thus, for pipes with OIT values longer than 20 minutes, the OIT test is the appropriate choice.

It is important to recognize that the single OIT value on the unaged pipes cannot totally reflect the performance of antioxidants, since certain antioxidants can produce a high OIT value at the test temperature of 200°C. In order to properly assess the antioxidant package, the depletion rate of antioxidants must also be determined. For QA/QC purposes, the corrugated pipe should be incubated in either air or water at a selected elevated temperature to accelerate the oxidation reactions. Specimens should be taken from the incubated pipe at given time intervals for OIT evaluation to establish a decrease trend. The duration of such incubation probably should not be longer than three months. The test conditions, including incubation temperature, duration of the incubation and percent OIT retained, should be specified by correlating to a long-term durability test that yields an oxidation resistance greater than 100 years.

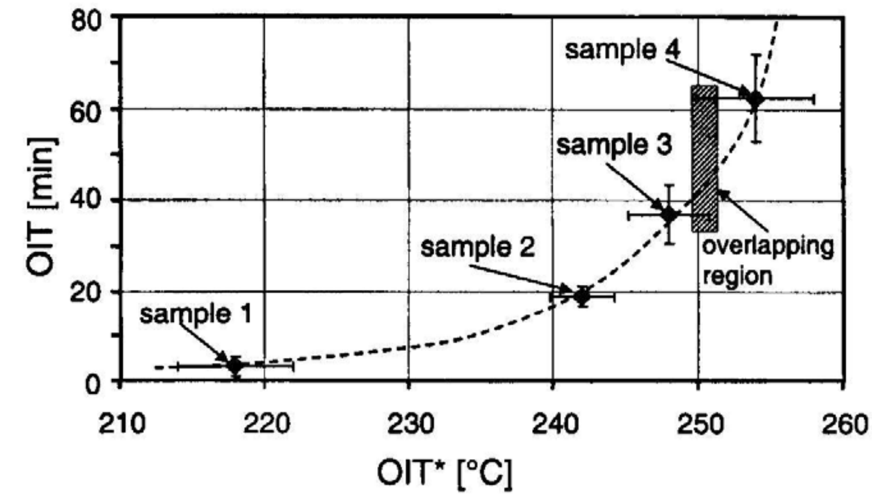

Figure 17 – Correlation between OIT and IT of four polyethylene grades

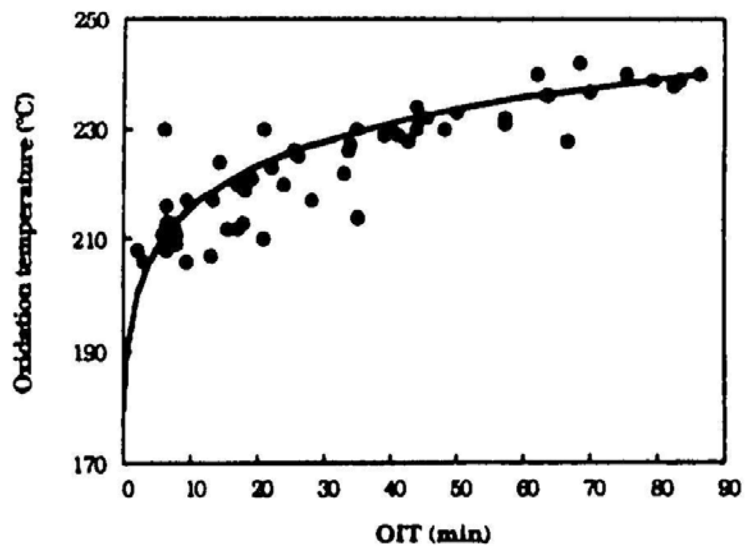

Figure 18 – Correlation between IT and OIT of
a type of antioxidant package

4.3 Accelerated Oxidation Tests

The lifetime of antioxidants and corrugated pipes can be predicted using temperature accelerated tests. The most important parameter in the acceleration test is that the incubation environment should reflect the field condition of the pipe. For corrugated drainage pipes, water saturated soil should surround the outside of the pipe and circulating water should be inside the pipe. The corrugation should be filled with static water. Such extensive experimental setup is not designed for QA/QC tests, but is for research to establish reference points which can then be correlated to the simplified QA/QC aging tests.

Two simplified accelerated oxidation tests were used to evaluate the depletion of antioxidants in the corrugated pipes. The purpose of these two tests is to illustrate the test procedures and analyses that are incorporated into the antioxidant test method, FM 5-574, entitled “Prediction the Antioxidant Lifetime in HDPE Corrugated Pipes” which is included as Appendix C of this report. However, it needs to be emphasized that an aging study, even under accelerated aging environments, generally requires over 12 months of testing time. The short duration of this project can only generate very limited data that are insufficient to predict the lifetime of antioxidant in the pipes used in this laboratory study.

4.3.1 Accelerated Oxidation in Air

Oven aging is the most widely used acceleration method to evaluate oxidation degradation of polymers. Test specimens are placed in a forced air oven at an elevated temperature to accelerate oxidation mechanisms. A minimum of three elevated temperatures should be utilized for the Arrhenius prediction method. In this laboratory test, a single elevated temperature was used for preliminary evaluation. Samples taken from the two corrugated pipes were incubated in a forced air oven at 85^{o}C. At intervals of 10, 30 and 60 days, specimens were taken from the crown and liner locations of the incubated pipe samples and were evaluated by the OIT test. The resulting OIT data are shown in Table 6. The OIT values at the liner and crown locations are very similar, and the average value of the two is used in the lifetime analysis in Section 4.4.

Table 6 – OIT value in forced air oven at 85^{o}C.

Material	Original OIT (min)	OIT of Incubated Samples (min)		
		10 days	30 days	60 days
P-1	31.35	30 (liner)	22.5 (liner)	23.9 (liner)
	30.44		24.7 (crown)	24.1 (crown)
P-2	26.17	24.7 (liner)	21.6 (liner)	18.8 (liner)
	26.61		23.4; 23.5 (crown)	19.2 (crown)

4.3.2 Accelerated Oxidation in Water

Certain types of antioxidants can be extracted from the material into surrounding liquid. In this laboratory test, water is used to evaluate the extractability of the antioxidants. Test specimens (liner only) are placed in a water bath at an elevated temperature to accelerate the extraction mechanism. Note that the oxidation rate in water is much slower than in the forced air oven, since the oxygen concentration in water is only 8% and in air is 20%. For lifetime prediction using the Arrhenius method, a minimum of three elevated temperatures should be utilized. In this laboratory test, a single elevated temperature was used for preliminary evaluation. Samples taken from the two corrugated pipes were incubated in a water bath at 85^{o}C. At interval of 30 days, incubated liner samples were removed from the bath and were evaluated by the OIT test. The resulting OIT data are shown in Table 7. The results indicate that the depletion of antioxidants is faster in water than air, which is consistent with the finding by Gedde's group. They found that antioxidant depletion is three time faster in water than in air (Smith, et al. 1992).

Table 7 – OIT value in water bath at 85^{o}C.

Material	Original OIT (min)	OIT of Incubated Samples After 30 days (min)
P-1	31.35	16.75
	30.44	
P-2	26.17	14.5
	26.61	

4.4 Methodology to Predict Lifetime of Antioxidants

Due to the short duration of the incubation, the depletion rate of antioxidant cannot be confidently predicted. However, the concept of the method is presented by adopting the activation energy value obtained from the HDPE geomembranes (Hsuan and Guan, 1998).

Step 1: Determine the depletion rate of antioxidants at each of the incubation temperatures (minimum of three temperatures). In this test, only one temperature at 85°C was performed. The data are plotted in (OIT) versus incubation time, as shown in Figure 19. A linear relationship can be generated, as indicated by Equation 11. The slope of the curve represents the depletion rate of antioxidants. Note that the slope in Figure 19 is not applicable for long-term prediction due to the extremely short incubation time.

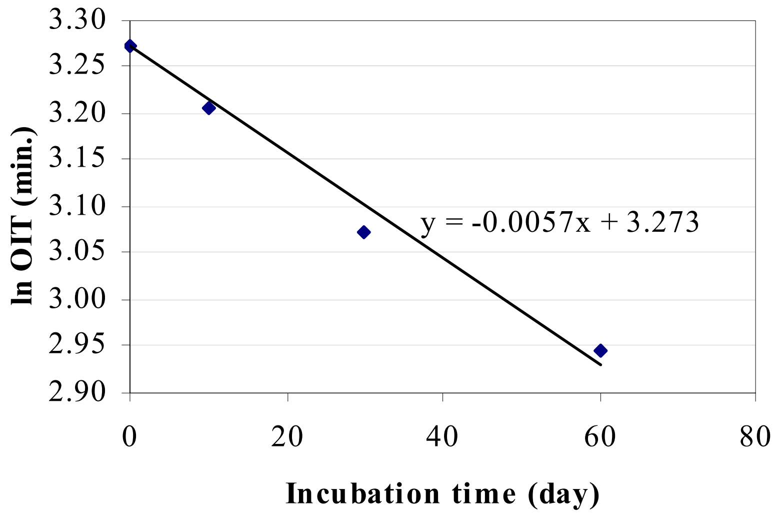

Figure 19 – Changes in OIT value with incubation time at 85°C forced air.

$$OIT = P^* \exp(- S^*t) \qquad (11)$$

where:

OIT = OIT time (min.)
P = original OIT of the geomembrane (min.)
S = OIT depletion rate (min./day)
t = incubation time (days)

Step 2: Use Arrhenius plots to predict the antioxidant depletion rate at site specific temperature, such as 20°C. Since the Arrhenius plot requires a minimum of three incubation temperatures, as shown in Figure 20, the activation energy obtained from the geomembrane is adopted to illustrate the prediction method.

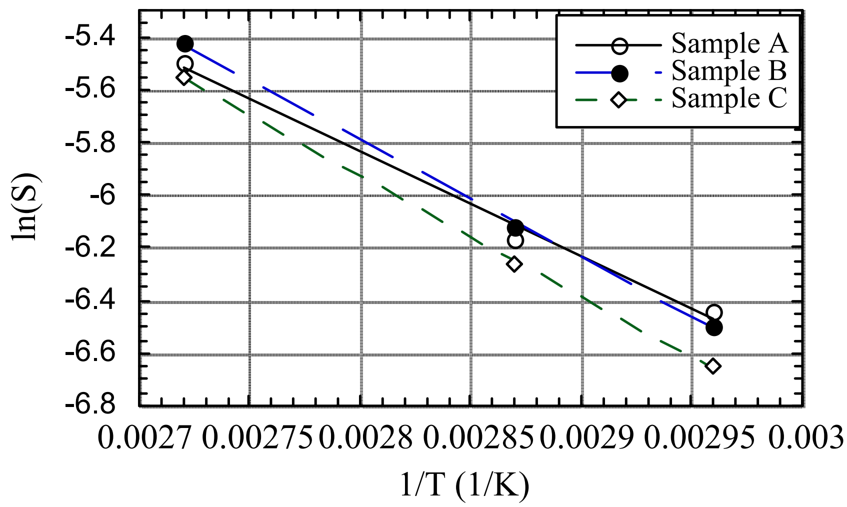

Figure 20 – Arrhenius plot for antioxidant depletion rate in three HDPE geomembranes at three different incubation temperatures

The Arrhenius Equation is represented in Equations (12) and (13)

$$S = A*\exp(-E/RT) \tag{12}$$

$$\ln(S) = \ln(A) + (-E/R)*(1/T) \tag{13}$$

where:

S	=	OIT depletion rate
E	=	Activation energy of the antioxidant depletion reaction under this test condition (kJ/mol)
R	=	gas constant (8.31 J/mol.K)
T	=	test temperature in absolute Kelvin (degrees K)
A	=	constant

The (-E/R) value obtained from Figure 20 is (-3835.1). The new (A) value is calculated based on new S and T values obtained in this test, as shown in Equations (14) and (15).

$$\ln(0.0057) = \ln(A) +(-3835.1)*(1/358) \tag{14}$$

$$\ln A = 5.55 \tag{15}$$

Now, determine the antioxidant depletion rate (S) at 20^{o}C, as illustrated in Equations (16) and (17)

$$\ln(S) = 5.55 – 13.1 = -7.5 \tag{16}$$

$$S = 0.00053 \tag{17}$$

Using the obtained depletion rate, the required time to deplete all the antioxidants in the coupons at 20°C was calculated using Equation (11). However, before proceeding with the calculation, a boundary condition must be established. This is the intrinsic OIT values that a pure unstabilized (i.e., no antioxidants) HDPE resin can possess in the OIT test, which was measured to be 0.5 minutes for the geomembrane resin. The time requires reaching 0.5 minutes of OIT time at 20^{o}C will be 21 years under the constant forced air environment.

4.5 Summary of Antioxidant Evaluation

The preliminary study on oxidation resistance of two HDPE corrugated pipes was evaluated via the depletion of antioxidants under water and air environments. Due to the time limit of this study, the lifetime of the antioxidants in the pipe cannot be confidently predicted. The lifetime prediction method presented in this test protocol is merely to illustrate the procedure and does not represent the performance of antioxidants in current corrugated pipes. However, the test data did indicate that the depletion of antioxidants proceeded much faster in water than in air.

Based on the laboratory evaluation on the antioxidant of the pipe and published literatures, a Florida Method of Test FM 5-574 was developed to measure accelerated oxidation of corrugated pipes. The test method is included as Appendix C of this report.

5.0 LABORATORY TESTS TO EVALUATE LONG TERM DESIGN PARAMETERS OF HDPE CORRUGATED PIPES

5.1 Introduction

The current design parameters specified by AASHTO Section 17 is shown in Table 8.

Table 8 – Mechanical Properties for Design HDPE Corrugated Pipe

Short Term Properties		50-year Long Term Properties	
Tensile Strength	Modulus of Elasticity	Tensile Strength	Modulus of Elasticity
3,000 psi	110,000 psi	900 psi	22,000 psi

The short term tensile strength and modulus of elasticity are taken from the material specification ASTM D3350 based on the cell class of 335400C. Using compressive molded plaques and not the finished pipe, the extrusion processing effects are not present. A part of this section of the laboratory tests is to investigate the possible differences in mechanical properties between compressive molded plaques and actual pipe materials.

For the long term property values, the AASHTO Section 17 states that “these values are derived from hydrostatic design bases (HDB) and indicate a minimum 50-year life expectancy under continuous application of the tensile stress”. Thus, the values listed in Table 8 were predicted under a creep mode. Since HDB testing was removed from the AASHTO Section 18 Bridge specification after 1996, the verification of the long term properties is questionable. Furthermore, the HDB test is not the appropriate test to evaluate corrugated pipes, since corrugated pipes are not subjected to constant internal pressure during service.

In this project, the alternative creep test is presented to determine the long-term tensile strength of the pipe. In addition, the long-term modulus value is evaluated based on stress relaxation mode instead of creep mode to reflect the in-situ condition of the pipe.

5.2 Tensile Properties of Pipes

The short term tensile strength listed in Table 8 is obtained from test specimens taken from compression molded plaques of pure resins; hence, effects of the pipe manufacturing process and the carbon black additives on the tensile properties are not considered. For the evaluation the tensile properties of the finished pipe, the liner part of the pipe is utilized for the test. ASTM D638 was used to test the pipe liner. Depending on the width of the liner between two junctions, either Type VI or V die shall be used. Table 9 shows the appropriate types of dies to be used to evaluate tensile properties of the pipe liner. (The individual test values are included as Appendix G of this report). The tensile specimens shall be oriented along the longitudinal axis of the pipe. Both type IV and V tests shall be performed at a strain rate of 2 inch/min. The gauge lengths are 2.5 inches and 0.3 inch for Type IV and Type V tests, respectively.

Table 9 – Type of die used in ASTM D 638 for different pipe diameters

Pipe Diameter (inch)	Type of Die used in ASTM D 638
18 to 42	Type V
48 to 60	Type IV

A comparison of tensile properties between molded plaque and pipe liner was carried out pipes P-1 and P-2. Table 10 shows the average tensile strength value of the tests. The data in Table 10 indicate that the tensile strength of Type V die is slightly higher than that of Type IV. The factor is approximately 1.04. In addition, the tensile strength of the pipe liner is slightly lower than that of the corresponding molded plaque based on Type V tensile tests. The difference between these materials is not the same for pipes P-1 and P-2. This suggests that the tensile strength is affected by the pipe manufacturing process.

Table 10 – Average tensile yield strength from molded plaque and pipe liner

Test Material	Type IV	Type V
P-1 (plaque)	4043	4155
P-1 (liner)		3625
P-2 (plaque)	3688	3867
P-2 (liner)		3578

5.3 Long-term Tensile Strength

As stated in Section 5.1, the 50-year long-term tensile strength of 900 psi was obtained using the HDB test (ASTM D 2837). The test provides the procedure to extrapolate test data to 50 years. However, the HDB test does not reflect the service performance of the corrugated pipe, and the test cannot be performed on the corrugated pipes. Therefore, an alternative method shall be employed to assess the long term tensile strength of corrugated pipes.

A new test, Florida Test Method FM 5-575 entitled, "Creep Rupture of Corrugated Pipe Liner Tensile Specimens", basically follows the concepts of ASTM D 2018. The test method is included as Appendix D of this report. The appropriate type of tensile specimens (see Table 9) shall be removed from the liner part of the corrugated pipe in the orientation parallel to the longitudinal axis of the pipe. The un-notched tensile specimens are subjected to a range of applied stresses in order to establish the stress-failure time curve in a water or air environment. Elevated temperatures from 50 to 80^{o}C can be used to accelerate the creep mechanisms.

Figures 21 and 22 are published data on hydrostatic burst test results of HDPE smooth pipes (Popelar et al., 1991). The burst tests were performed at four different temperatures and their stress versus failure time were plotted in a log-log scale, as shown in Figure 21. By applying the appropriate shift factors, the elevated failure points were shifted to 20^{o}C, as shown in Figure 22. The resulting master curve at 20^{o}C consisted of data extending to 100 years. The same methodology can be applied to corrugated pipe using the tensile creep data. The prediction procedures are described in the Florida Test Method FM 5-576 entitled, "Determining the Long-term Tensile Strength of HDPE Corrugated Pipe" and is included as Appendix E of this report.

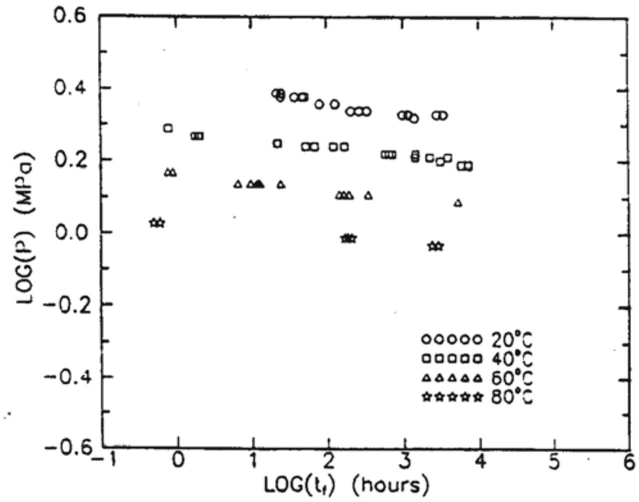

Figure 21 – Hydrostatic burst pressure test data on smooth HDPE pipes

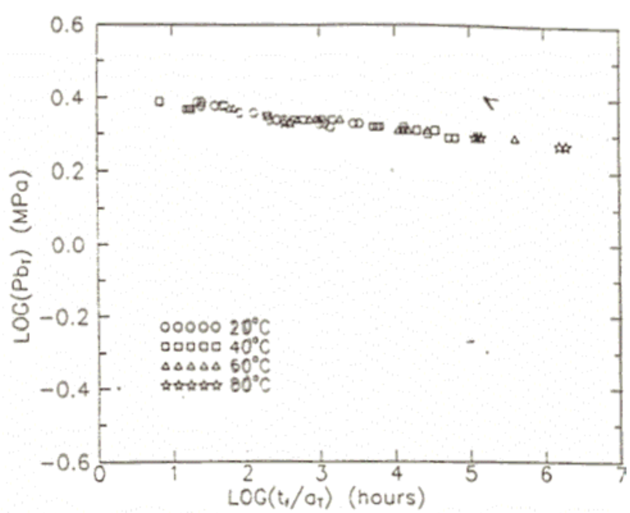

Figure 22 – Obtaining master curve by shifted data in figure 21 to 20^oC

5.4 Flexural Modulus of Pipes

The flexural modulus listed in Table 8 represents the 2% secant modulus of a 3-point bending test according to ASTM 790, Method 1-Procedure B. The test material is obtained by compression molded resin material not the finished pipe. However, the 3-point bending test is not suitable to evaluate pipe liner of different size of diameters. For small diameter pipes (less than 24 inches), the length of the liner between corrugation is too short for a 3-in long bending specimen. In addition, the liner thickness for small diameter pipes is too thin to be tested using the 2-in span distance as defined in the ASTM 790.

For the finished pipes, the method to evaluate the flexural modulus is ASTM 2412. In Appendix X2 of the standard method, the relationship between pipe stiffness and flexural modulus at a given deflection is expressed in Equation (18).

$$EI = (SF) = 0.149r^3 \, (PS) \qquad (18)$$

Where:

E = flexural modulus (psi)
I = moment of Inertia = $t^3/12$ (in^3)
t = wall thickness of the pipe (in)
r = radius of the pipe (in)
PS = pipe stiffness = $F/\Delta y$ (as determined by test) (lb/in/in)
F = load per liner inch (lb/in)
Δy = vertical deflection (in)

A comparison was made on the difference between 2% secant modulus and flexural modulus at 2% vertical deflection using pipe P-2. A force versus deflection curve of P-2 was provided by the pipe manufacturer. The inner diameter of the pipe is 24 inches and the length of the test pipe is 27 inches. To achieve 2% vertical deflection, Δy shall be 0.48-inch. Using Equation (18), the calculated flexural modulus value for P-2 is 109,000 psi, whereas 2% secant modulus of the P-2 pipe plaque was measured to be 118,000 psi. These two flexural modulus values are relatively similar considering that they are obtained from two very different tests.

5.5 Long-term Flexural Modulus

For the evaluation of flexural modulus of finished pipes, the parallel plate test (ASTM D 2412) is the only standard available. The test should be carried out at deflection of 5%, which is the maximum allowable deflection value under a stress relaxation mode to reflect the condition of the pipe in the field throughout the service life. However, the test would be impractical for large diameter pipes, particularly so when testing utilizes a series of elevated temperatures. An alternative test to assess flexural modulus of finished pipes should be investigated. Gabriel and Goddard (1999) developed a curved beam test using a half pipe specimen to simulate the parallel plate test. They also performed stress relaxation tests on seven different half pipes using the curved beam test. However, the tests were carried out at room temperature, making a 100-year exploration questionable.

Due to the short duration of the project, long term stress relaxation test based on ASTM D 2412 was not performed. On the other hand, stress relaxation tests were performed using Dynamic Mechanical Analyzer (DMA) to illustrate the concept of Time-Temperature Superposition (T-T-S) from which a master curve at the site temperature can be obtained.

DMA tests were performed using pipe liner material from pipe P-2. The specimen was clamped between two mechanical arms, as shown in Figure 23. A shear bending was introduced to the test specimen; the deformation of the test specimen is illustrated in Figure 24. The "X" is the bending deformation which was 0.04%.

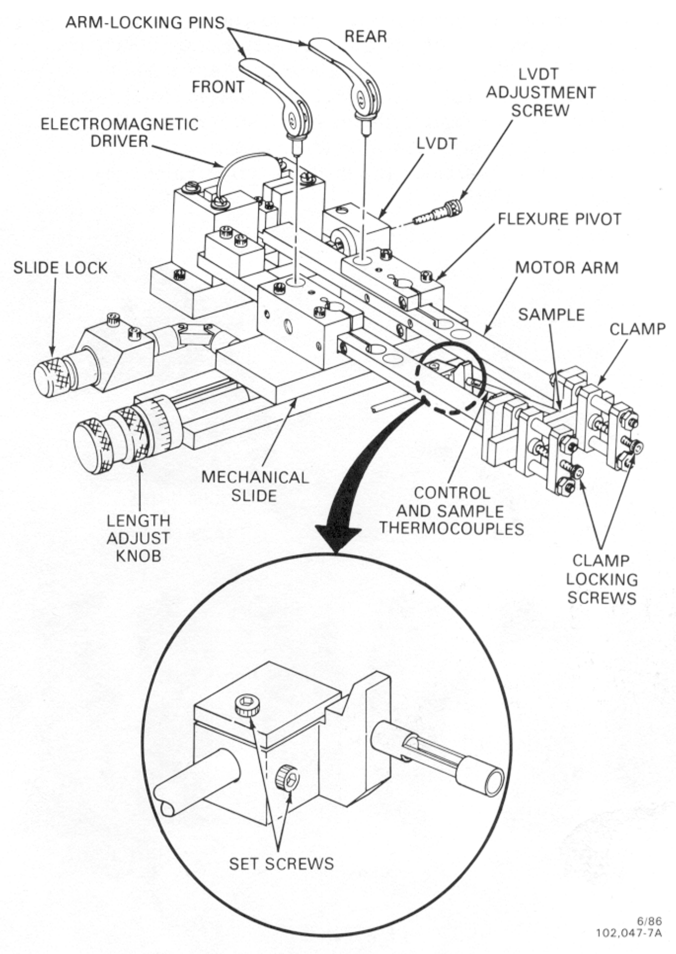

Figure 1.6
DMA Internal Components

Figure 23 – Configuration of specimen clamping system in DMA

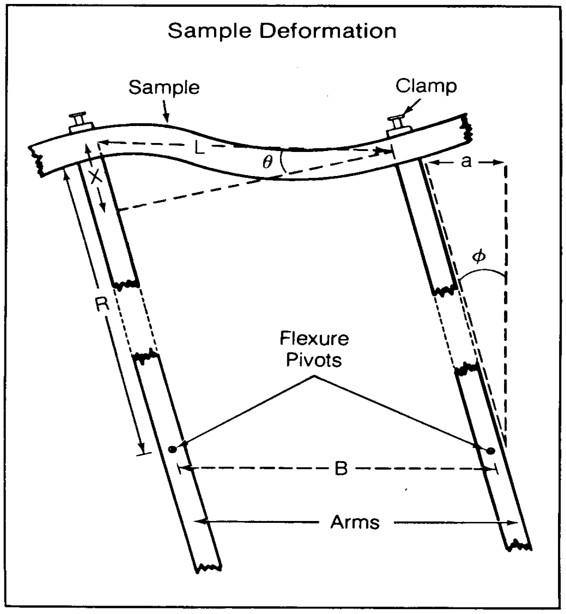

Figure 4.6
Sample Deformation

Figure 24 – Deformation of the test specimen in DMA

The stress relaxation tests were carried out at temperatures from 27.5 to 65°C at 7.5°C increments. The duration of the each test was 10 hours. Figure 25 shows the stress relaxation curve at each temperature. The six curves were then shifted using the T-T-S software provided by the DMA manufacturer (TA Instrument). The resulting master curve at 27.5°C is shown in Figure 26. In this set of tests, the master curve was extended to 1.4 years. The same set of data was also shifted using Popelar factors and shifted data are shown in Figure 27. The master curve only extended to 1000 hours, which is much shorter than the T-T-S method.

In the second set of tests, the duration of each stress relaxation test was increased to 16.7 hours. The resulting master curve at 27.5°C is extended to 13 years, as shown in Figure 28. The long-term relaxation modulus values were 16% and 17.6% at 1.4 and 13 years, respectively. Table 11 shows the short term and long term modulus values. By extrapolating the curve in Figure 28 to 100 years, the long-term modulus value is approximately 17,000 psi.

Table 11 – Flexural Modulus obtained from DMA tests

Test-1		Test-2		
Initial	1.4 years	Initial	13 years	100 years (extrapolated)
113,800 psi	18,250 psi	126,700 psi	22,300 psi	17,000 psi

5.6 Summary of Long-term Mechanical Properties

The current specified 50-year properties were evaluated based on HDB method, which is unsuitable for use on corrugated pipes. In addition, short term properties were according to the resin cell class defined in the ASTM D 3350, not the finished pipes. Laboratory tests were performed to assess the tensile strength and 2% flexural modulus between compression molded pipe plaque and finished pipe. Their differences are relatively small; however, values from the finish pipe are approximately 10% lower than the corresponding mold plaque material.

For long-term properties, tests should be performed using finished pipes. Two new test methods (FM 5-575 and FM 5-576) were developed to assess long-term tensile strength of corrugated pipe liner. For the long-term flexural modulus value of the pipe, the parallel plate test (ASTM D 2412) is the only standard test and should be used. The test should be performed under a stress relaxation condition at 5% deflection, at a series of elevated temperatures, as described in FM 5-577 and included in the Appendix F of this report. At this time, the test is limited to pipes 24 inch diameter and less for practical purpose.

For 100-year properties, both tensile and flexural tests should utilize elevated temperatures to accelerate the viscoelastic properties and then extrapolate to the site temperature of 20^{o}C using either the T-T-S or Popelar shift factors. The DMA results suggest that Popelar shift factors predicted a shorter time than the T-T-S due to bi-axial shift.

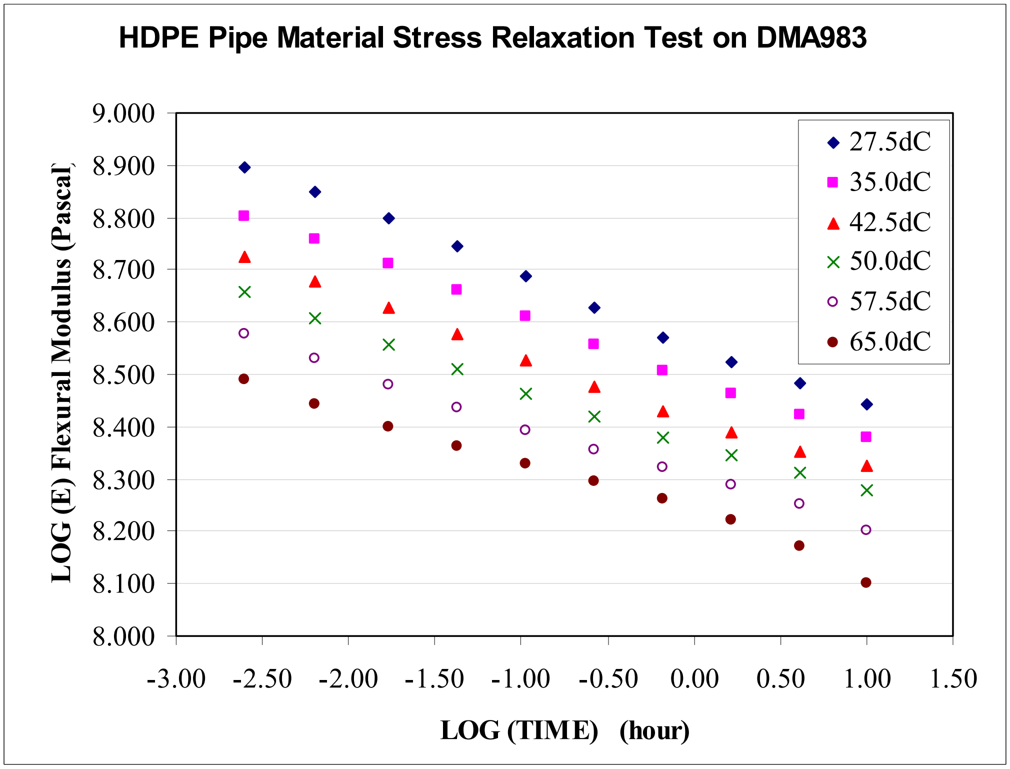

Figure 25 – Stress relaxation curves resulted from the DMA test-1

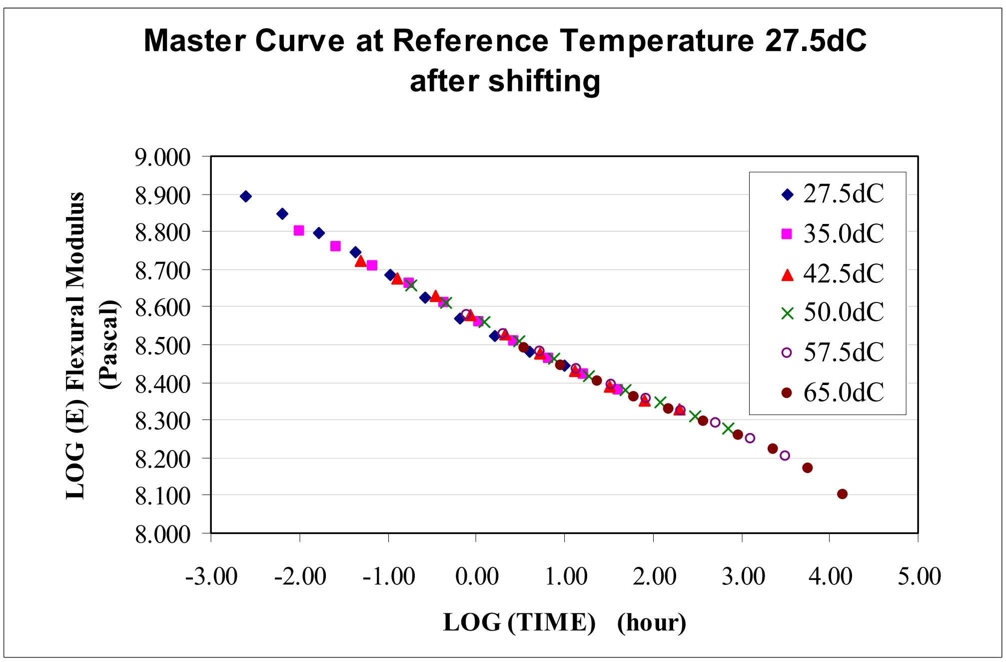

Figure 26 – Master curve at 27.5°C after shifted using the T-T-S software

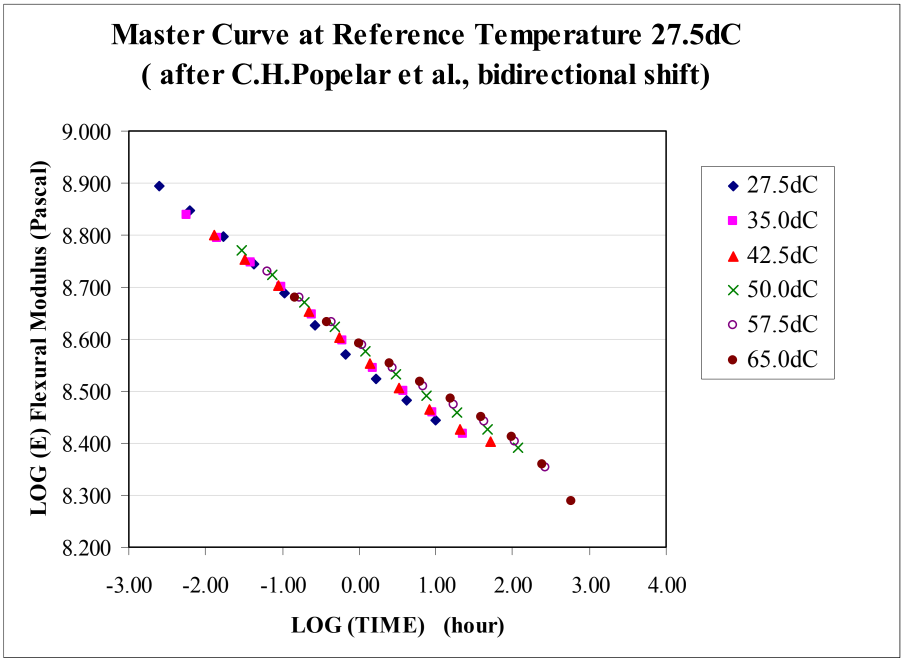

Figure 27 - Master curve at 27.5°C after shifted using Popelar factors

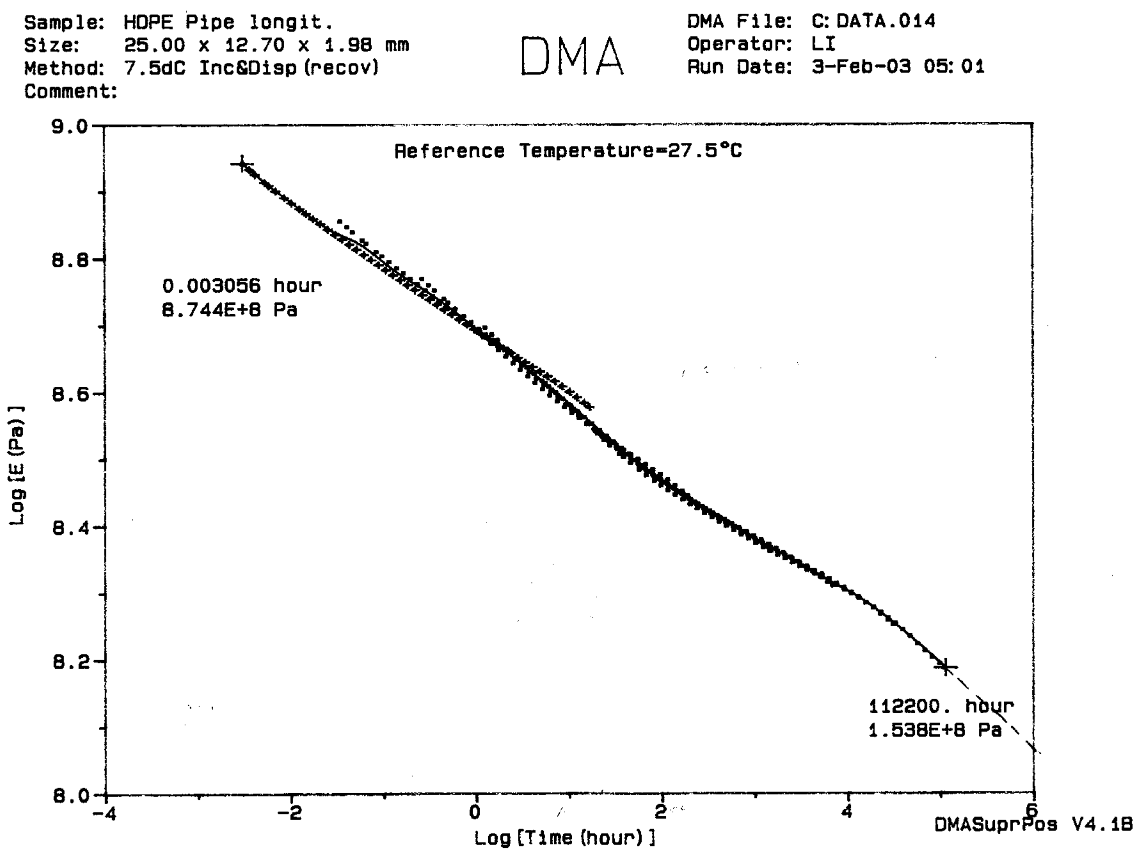

Figure 28 – Master Curve at 27.5°C from DMA test-2

6.0 SPECIFICATION

The specification for HDPE corrugated pipes to assure 100-year performance is summarized in this section. The specification consists of two parts: an interim specification and a full specification. The details of the interim specification are presented in Appendix I as well as a separate stand alone document. The interim specification focuses on two major properties: stress crack resistance and antioxidant content and depletion rate. In the interim specification, each required test is based on go-and-no go criterion under specific test conditions. The specified values are determined using published data from other HDPE products.

In the full specification, four properties, stress crack resistance, oxidation degradation, long-term tensile strength and long-term flexural modulus are required. The details of the full specification are presented in Appendix J. For each property, a set of tests at different temperatures and/or stresses shall be performed so that the 100-year behavior of the pipe at site temperature of 20°C can be extrapolated and determined with greater confidence.

7.0 CONCLUSIONS

Four long-term material properties of HDPE corrugated pipes were investigated in the project. These four properties included stress cracking resistance of the pipe, antioxidant lifetime of the pipe, long-term tensile strength and long-term flexural modulus. Based on the results of this study, following are the conclusions:

<u>Stress crack resistance (SCR) of HDPE corrugated pipes</u>

i) SCR of the pipe liner is affected by the manufacturing processing
ii) Pipe junctions and longitudinal profiles (such as vent-hole) are susceptible to stress cracking.
iii) Stress crack growth mechanisms are very similar in water and 10% Igepal. The 10% Igepal solution was shown to accelerate the crack growth 1.7 times faster than water.
iv) Stress crack growth mechanisms in air are significantly different than in water and 10% Igepal. The crack growth rate in air is significantly slower than the other two.
v) Popelar shift factors can be applied to SCR test data at elevated temperatures to predict the SCR at lower site temperature.

<u>Antioxidants stability of HDPE corrugated pipes</u>

i) The lifetime of HDPE corrugated pipes is governed largely by the amount and type of antioxidants added.

ii) Between OIT and IT, the OIT is the appropriate test to assess antioxidant with value longer than 20 minutes.
iii) Due to solubility of antioxidants, the depletion of antioxidants is more severe in water than in air.

Long-term tensile strength and flexural modulus

i) The tensile strengths of pipe liners are slightly lower than the corresponding molded plaque.
ii) Creep rupture tests on pipe liner at elevated temperatures should be used to determine the long-term tensile strength.
iii) The flexural modulus of 3-point bend test from molded plaque and 2% modulus from parallel plate tests are relatively similar.
iv) Parallel plate test at 5% deformation under stress relaxation mode should be used to determine the long-term modulus.
v) The master curve generated from Popelar shift factors is more conservative than that from the time-temperature superposition method.

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APPENDIX A

Florida Method of Test
for Determining Slow Crack Growth Resistance of
HDPE Corrugated Pipes

Designation, FM 5-572

Florida Method of Test for Determining Slow Crack Growth Resistance of HDPE Corrugated Pipes

Designation, FM 5-572

1. SCOPE

   1.1 This test method is used to determine the susceptibility of corrugated pipe to slow crack growth under a constant ligament stress (CLS) in an accelerating environment.

   1.2 The test consists of three procedures to evaluate three different parts of the corrugated pipes which are pipe liner, corrugation/liner junction and longitudinal profile.

   1.3 This test method measures the failure time associated with a given test specimen at a constant, specified, ligament stress level.

   1.4 The values stated in inch-pound units are to be regarded as the standard. The values given in parenthesis are mathematical conversions to SI units, which are provided for information only and are not considered standard.

2. REFERENCED DOCUMENTS

   2.1 ASTM Standards:

   D638 Tensile Properties of Plastics

   D1600 Terminology for Abbreviated Terms Relating to Plastics

   D5397 Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test

   F1473 Test Method for Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins

   F2136 Standard Test Method for Notched Constant Ligament Stress (NCLS) Test to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe

   2.2 Other Documents:

   AASHTO (American Association of State Highway and Transportation Officials) Standard Specification M 294.

3. TEST METHOD

3.1 This test method subjects a dumbbell-shaped, notched or un-notched test-specimen to a constant ligament stress of 600 psi in the presence of a surface-active agent at an elevated temperature.

4. APPARATUS

4.1 Blanking Die. - A die suitable for cutting test specimens with holes to the dimensions and tolerances specified in Figures 1 and 2 for Types I and II, respectively. The Type 1 die shall be used for specimen thickness from 0.040 to 0.125 inch. The Type 2 die shall be used for specimen thickness from 0.126 to 0.25 inch.

4.2 Stress Crack Testing Apparatus. - A lever loading machine, with a lever arm ratio of 3:1 to 5:1 similar to that described in ASTM D 5397. Alternatively the tensile load may be applied directly using dead weights or any other method for producing a constant ligament stress. The bath solution temperature shall be set at 122 +/- 2 °F (50 +/- 1 °C).

(Testing apparatus is available from BT Technology, Inc. 320 N. Railroad Street, Rushville, IL 62681, Materials Performance, Inc. 2151 Harvey Mitchell Pkwy, S. Suite 208, College Station, TX 77840, Satec Systems, 900 Liberty Street, Grove City, PA 16127, or equivalent.)

4.3 Notching Device. - Notch depth is an important variable that must be controlled. Section 8.2.1 describes the notching procedure and type of apparatus used. The approximate thickness of blade should be 0.008 – 0.012 in (0.2 to 0.3 mm).

Note 1: A round robin was conducted to determine the effect of types of blades on the notch depth. In this study several types of steel blades (single edge, double edge etc.) from various manufacturers were used by the round robin participants. The round robin consisted of seven laboratories using 2 types of resins molded into plaques. The standard deviation of the test results within laboratories is less than +/-10 %.

(Notching apparatus is available from BT Technology, Inc. 320 N. Railroad Street, Rushville, IL 62681, Satec Systems, 900 Liberty Street, Grove City, PA 16127, or equivalent.)

4.4 Micrometer (or caliper) capable of measuring to +/- 0.0005 in (+/- 0.0127 mm).

4.5 Electronic scale for measuring shot weight tubes capable of measuring to +/- 0.0002 lbs. (0.1 g).

4.6 Timing device capable of recording failure time to the nearest 0.1 h.

5. REAGENT

The stress cracking reagent shall consist of 10% nonylphenoxy poly (ethyleneoxy) ethanol (Igepal CO-630 from Rhone-Poulenc or equivalent) by volume in 90% de-ionized water. Solution level is to be checked daily and de-ionized water used to keep the bath at a constant level.

6. PROCEDURE A – Pipe Liner Test

6.1 Specimen Preparation:

6.1.1 Test specimens are to be die cut from the inner liner of the corrugated pipe. The specimens shall be oriented along the longitudinal axis of the pipe, as shown in Figure 3.

6.1.2 The die cut shall start from the inner liner surface (i.e., the inner liner surface shall face up towards the die).

Note 2: Select the appropriate die (either Type I or II) for the test (see Section 4.1)

6.1.3 Five specimens shall be taken from the test pipe. Specimen shall be cut from the same circumferential section of the test pipe at five locations of 70^{o} apart from each other.

6.1.4 The average thickness of each test specimen shall be determined by averaging three thickness measurements of the constant neck section.

6.2 Notching

6.2.1 Specimens shall be notched across the center of the constant neck section on the inner liner surface, as shown in Figure 4. The notch shall be cut at a maximum rate of 0.2 inch per minute (5.0 mm per minute) to a depth (a) according to Tables 1 and 2. Notch depth shall be controlled to +/- 0.001 in (+/- 0.025 mm) by measuring the notch depth with a microscope.

Note 3: The notch depth is determined based on fracture intensity factor being the same as a specimen with thickness (T) of 0.075 inch and depth thickness (a) of 0.015 inch under applied stress of 600 psi. The applied stress is calculated using the ligament thickness as described in next section of this test method.

6.2.2 No single razor blade shall be used for more than 10 test specimens.

Table 1 – Notch Depth as a Function of Average Thickness for Type I Die

Specimen Average Thickness (T) (inch)	Notch Depth (a) (inch)
0.075 – 0.085	0.015
0.086 – 0.125	0.016

Table 2 – Notch Depth as a Function of Average Thickness for Type II Die

Specimen Average Thickness (T) (inch)	Notch Depth (a) (inch)
0.126 – 0.25	0.016

6.3 Calculation of Test Load:

6.3.1 For each specimen, measure the reduced section width (W), thickness (T), and notch depth (a) to the nearest 0.001 in using a micrometer (or caliper) and the microscope.

6.3.2 At each loading point, using the equation (1), determine the load (P) that must be hung on the appropriate lever arm to produce the required ligament-stress. The necessary load shall be prepared accurately enough that the ligament-stress does not vary by more than +/ - 0.5%. The appropriate applied load is:

$$P = \frac{SW(T-a) - C.F.}{M.A.} \qquad (1)$$

Where:

P = *load to be applied to the lever arm (lbs.)*
S = *specified ligament stress (600 psi)*
W = *cross sectional width of the test specimen (in).*
T = *thickness of the test specimen (in).*
a = *the depth of the notch (in)*
$C.F.$ = *correction factor for individual lever weights, based on unit average of lever arm minus weight of sample holding rod. (lbs.).*
$M.A.$ = *mechanical advantage of the test apparatus lever.*

6.3.3 Each test weight so determined is to be labeled (or otherwise correlated to each test position) and applied to the appropriate lever arm on the test apparatus.

7. Test Procedure B – Corrugation/Liner Junction Test

7.1 Specimen Preparation:

7.1.1 The Type II die shall be used to die cut specimens from the junction region of the pipe. The junction shall be positioned within the constant neck section of the die. If the valley width is narrower than the constant neck section of the Type II die, both sides of the junction can be tested simultaneonsly, as shown in Figures 5 and 6. When the length of the valley is longer than the constant neck section, each junction shall be tested separately, as shown in Figures 7 and 8.

Note 4: The specimen shall be removed from the die carefully to avoid imposing stress at the junction.

7.1.2 For each junction, five specimens shall be cut from the same circumferential section of the test pipe but at locations of 70° apart from each other.

7.1.3 Measure the thickness of the liner section of the specimen. Three measurements shall be recorded and the lowest value shall be used in the applied load calculation.

7.2 Calculation of Test Load:

7.2.1 For each specimen, measure the reduced section width (W), and the lowest liner thickness (T).

Note 5: for the thickness (T) value, refer back to Section 7.1.3.

7.2.2 At each loading point, using the equation (2), determine the load (P) that must be hung on the appropriate lever arm to produce the required ligament-stress. The necessary load shall be prepared accurately enough that the ligament-stress does not vary by more than +/ - 0.5%. The appropriate applied load is:

$$P = \frac{SWT - C.F.}{M.A.} \tag{2}$$

Where:

P = *load to be applied to the lever arm (lbs.)*
S = *specified stress (600 psi)*
W = *cross sectional width of the test specimen (in).*
T = *thickness of the test specimen (in).*
$C.F.$ = *correction factor for individual lever weights, based on unit average of lever arm minus weight of sample holding rod. (lbs.).*
$M.A.$ = *mechanical advantage of the test apparatus lever.*

7.2.3 Each test weight so determined is to be labeled (or otherwise correlated to each test position) and applied to the appropriate lever arm on the test apparatus.

8 Procedure C – Longitudinal Profile Test

8.1 Definition of longitudinal profile - Longitudinal profile(s) includes features that run along the longitudinal axis of the pipe in either continuously or repeating in regular intervals. These features may be a part of the pipe design (for example vent holes or mold line) or those generated by extrusion defects.

8.2 Speciment perparation:

8.2.1 The Type II die shall be used to die cut specimens from the profile region of the pipe. The orientation of the specimen shall align with the circumferencial of the pipe. The profile feature shall be positioned at the center position of the constant neck section of the die.

8.2.2 For vent-hole profile, the vent-hole shall be positioned at the center of the specimen. The crown-portion of the vent hole shall be removed, as shown in Figure 9.

8.2.3 For each profile, five specimens shall be cut from the test pipe at locations of 4 corrugations apart from each other.

8.2.4 For vent-hole specimen, measure the thickness of the liner portion (T_L) of the vent hole. Two measurements shall be recorded and the lowest value shall be used in the applied load calculation.

8.2.5 For other longitudinal profile, such as mold line, the thickness of the constant neck section of the specimen shall be measured. Three measurements shall be recorded and the lowest value shall be used fin the applied load calculation.

8.3 Calculation of Test Load:

8.3.1 For each specimen, measure the reduced section width (W), and the lowest thickness form the specimen (T) or liner portion (T_L).

Note 6: for the thickness (T_L) and *(T) value, refer back to Section 8.2.4 and 8.2.5, respectively.*

8.3.2 At each loading point, using the equation (3) or (4), determine the load (P) that must be hung on the appropriate lever arm to produce the required ligament-stress. Equation (3) is applied to vent-hole profile only; all other longitudinal profiles shall use Equation (4) to calculate the load. The necessary load shall be prepared accurately enough that the ligament-stress does not vary by more than +/ - 0.5%. The appropriate applied load is:

$$P = \left(\frac{SWT_L - C.F.}{M.A.} \right) - (BS) \tag{3}$$

$$P = \left(\frac{SWT - C.F.}{M.A.} \right) - (BS) \tag{4}$$

Where:

P = *load to be applied to the lever arm (lbs.)*
S = *specified stress (600 psi)*
W = *cross sectional width of the test specimen (in).*
T = *thickness of the test specimen (in).*

T_L = *thickness of the test specimen (in).*
$C.F.$ = *correction factor for individual lever weights, based on unit average of lever arm minus weight of sample holding rod. (lbs.).*
$M.A.$ = *mechanical advantage of the test apparatus lever.*
BS = *bending stress which varies with the profile of the pipe*

$$BS = \left(\frac{T/2}{R}\right)(E) \qquad (5)$$

R = *Inside radius of the pipe*
E = *Long-term modulus (20,000 psi)*

8.3.3 Each test weight so determined is to be labeled (or otherwise correlated to each test position) and applied to the appropriate lever arm on the test apparatus.

9 Testing*:*

9.1 Maintain temperature in the bath at 122 +/- 2 °F (50 ± 1°C).

9.2 Determine the weight to be placed on each specimen, and load the weight tubes with shot. Do not attach the shot tube to the lever arm.

9.3 Attach the specimens to the loading frame. Take care that bending the specimen does not activate the notch. Lower the specimen into the bath, and condition the specimens in the bath for at least 30 minutes.

9.4 Reset the specimen timer to zero.

9.5 Check that the weight is the correct weight for the particular specimen, and carefully connect the weight tube to the appropriate lever arm for the specimen. Apply the load gradually within a period of 5 to 10 s without any impact on the specimen.

9.6 Start the specimen timer immediately after loading.

9.7 Record the time to failure of each specimen to the nearest 0.1 h.

10 REPORTING RESULTS

Test report shall include the following information:

10.1 All details necessary for complete identification of the material tested (density, melt index, lot number, etc.).

10.2 Test information shall be recorded according to Table 3 for test Procedure A and Table 4 for test Procedures B and C.

10.3 Report the failure time for each of the five specimens and the arithmetic average of the five specimens.

Table 3 – Recommend Data Record Template for Test Procedure A

<table>
<tr><td colspan="7">Date:
Sample Identification:
Pipe Region being Evaluated:
Test Procedure:
Test Temperature:
Solution:</td></tr>
<tr><td>Applied Stress
(σ)
(psi)</td><td>Average Thickness
(T)
(in)</td><td>Notch Depth
(a)
(in)</td><td>Ligament Thickness
(T-a)
(in)</td><td>Specimen Width
(W)
(in)</td><td>Applied Load
(P)
(lb)</td><td>Failure Time
(t)
(hr)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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</table>

Table 4 – Recommend Data Record Template for Test Procedures B and C

<table>
<tr><td colspan="5">Date:
Sample Identification:
Pipe Region being Evaluated:
Test Procedure:
Test Temperature:
Solution:</td></tr>
<tr><td>Applied Stress
(σ)
(psi)</td><td>Minimum Thickness
(T)
(in)</td><td>Specimen Width
(W)
(in)</td><td>Applied Load
(P)
(lb)</td><td>Failure Time
(t)
(hr)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
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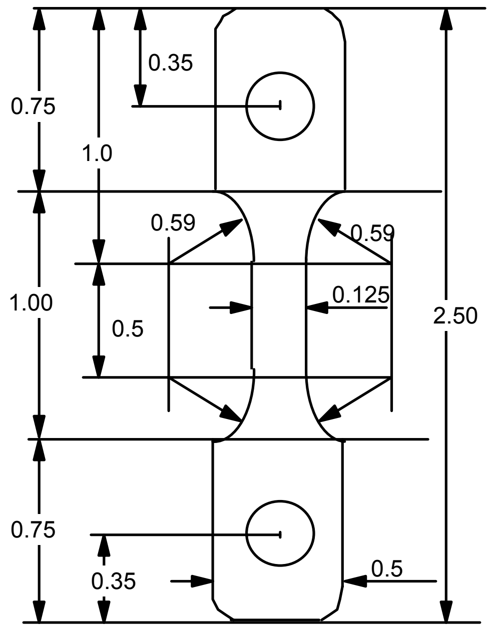
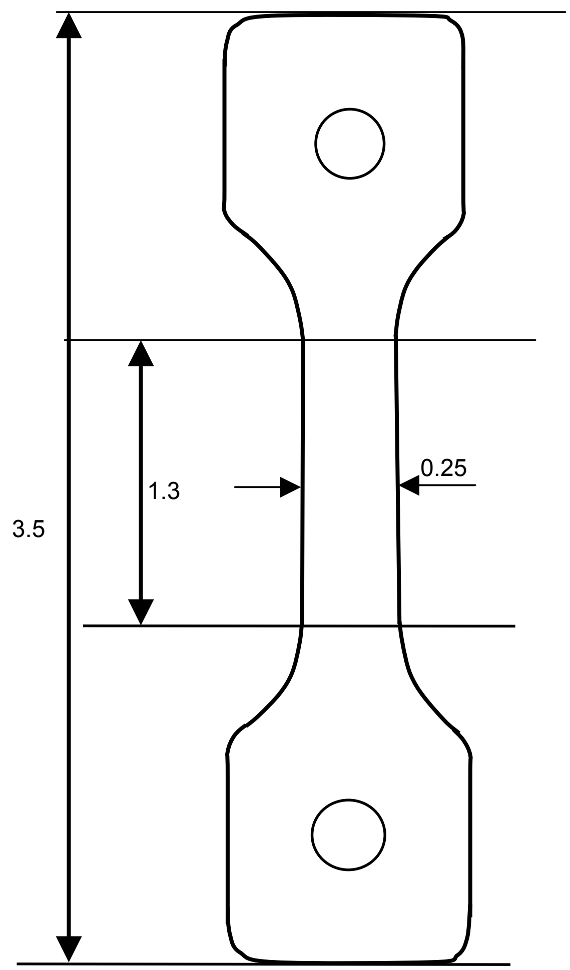


Note - Dimensions in inches to an accuracy of 0.005 inches

Figure 1. Specimen Geometry –Die Type I Dimensions

Note 7. The test specimen is intended to have the same geometry used for ASTM D 5397 specimens. The length of the specimen can be changed to suit the design of the test apparatus. However, there should be a constant neck section with length at least 0.5 in (13 mm) long.



Note - Dimensions in inches to an accuracy of 0.05

Figure 2. Specimen Geometry –Die Type II Dimensions

Note 8. The test specimen is intended to have the same geometry used for ASTM D 638 Type IV specimens. The length of the specimen can be changed to suit the design of the test apparatus. However, there should be a constant neck section with length at least 1.3 in long.

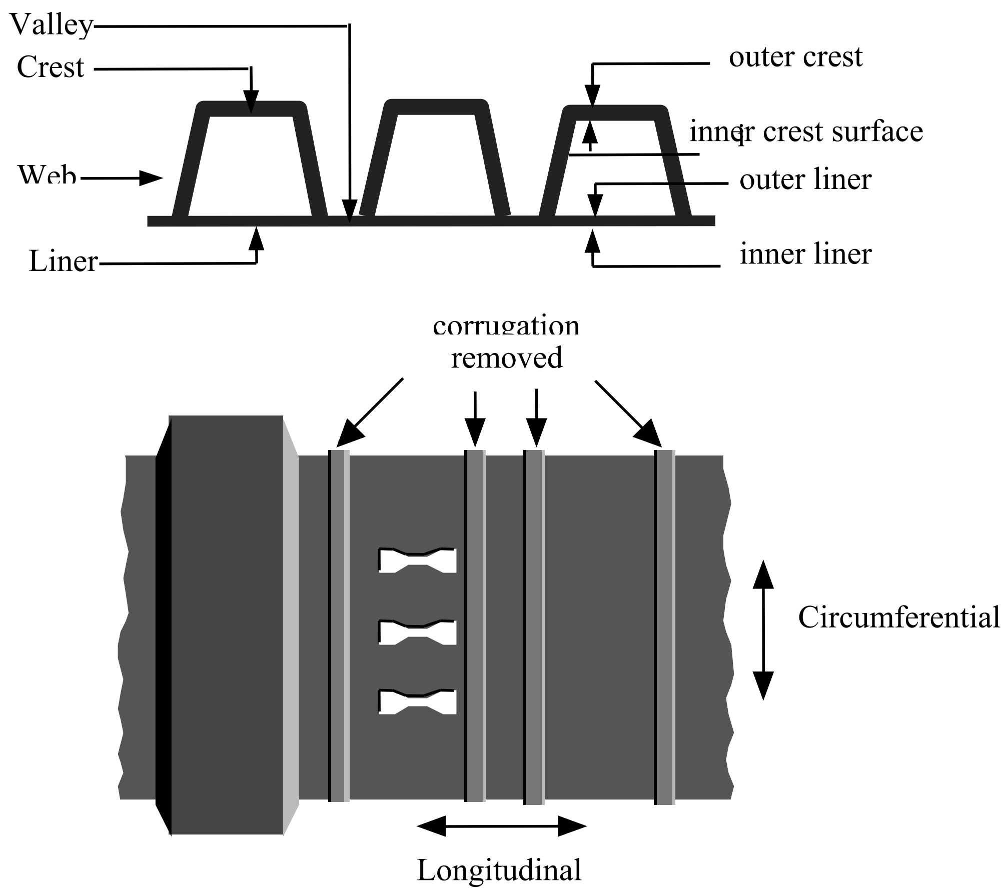


Figure 3 – Location of test specimens taken from the liner part of the pipe

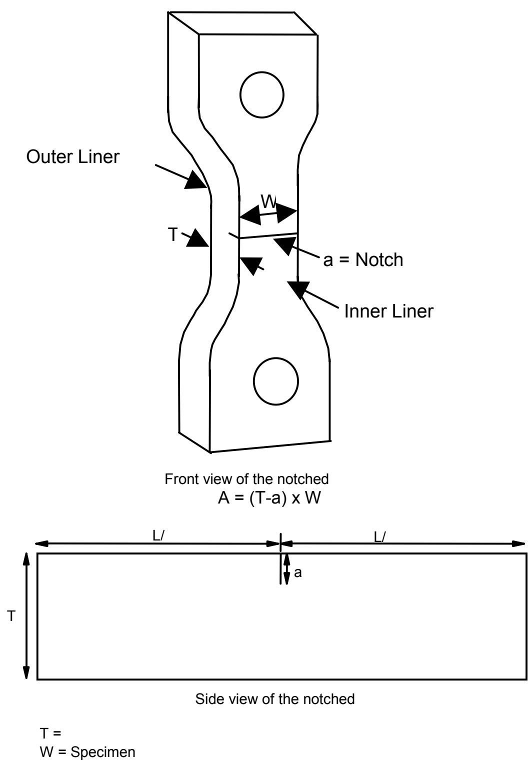


Figure 4 – Notch position with respect to the geometry of the specimen

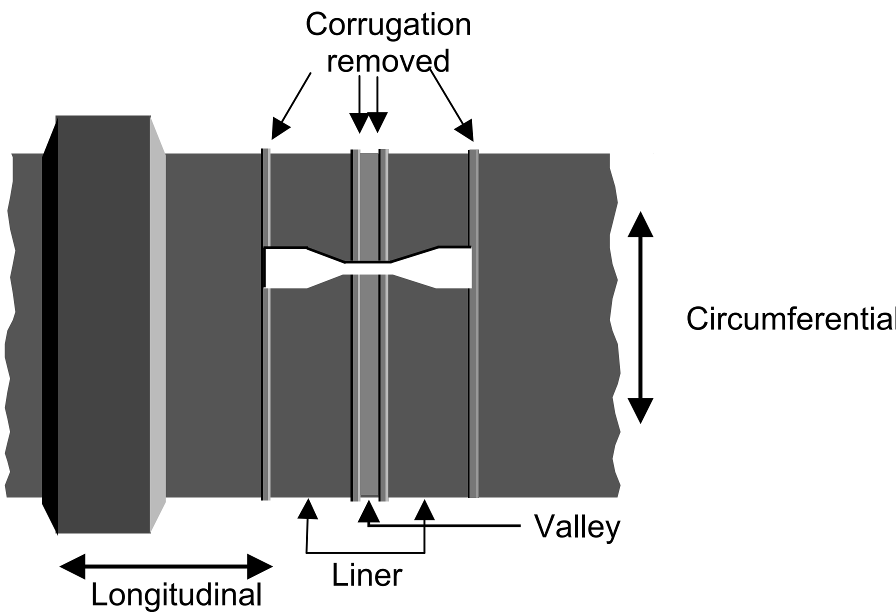


Figure 5 – Location of the test specimen when the width of valley is narrower than the constant neck section of the die.

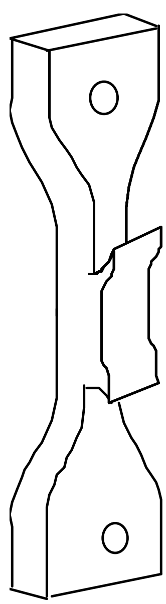


Figure 6 – A schematic diagram of the test specimen from Figure 4.

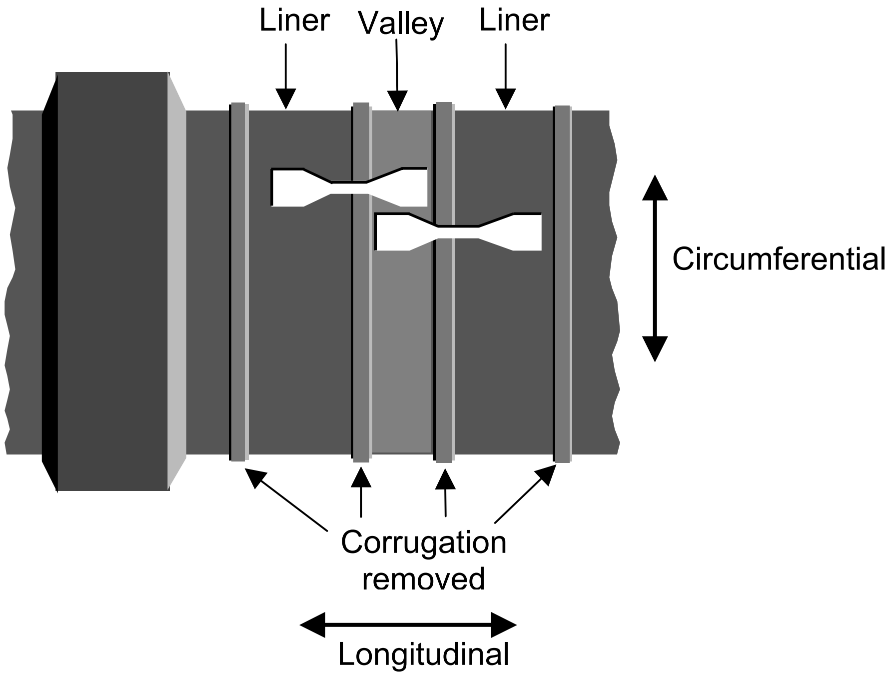


Figure 7 – Locations of the specimen taken from each side of the junction

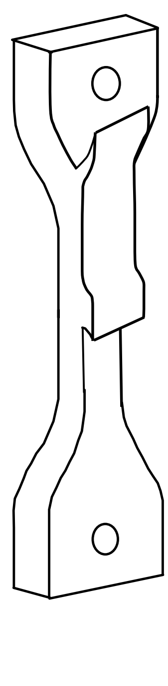


Figure 8 – A schematic diagram of the test specimen from Figure

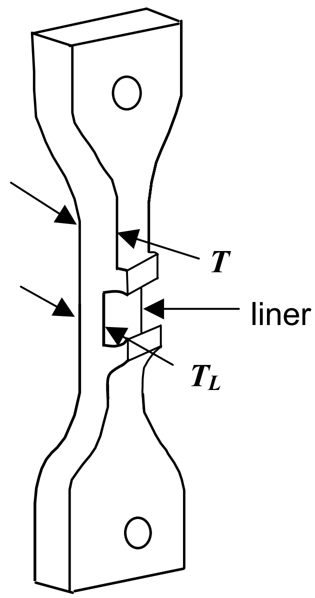


Figure 9 – A side-view of a vent hole test specimen with crown part being removed

APPENDIX B

Florida Method of Test for Predicting the Crack Free Service Life of HDPE Corrugated Pipes

Designation, FM 5-573

Florida Method of Test for Predicting the Crack Free Service Life of HDPE Corrugated Pipes

Designation, FM 5-573

1. SCOPE

1.1 This test method is used to predict the crack free service life of high density polyethylene corrugated pipes in view of Florida DOT 100-year design service life requirement.

1.2 This test utilizes data obtained from test method that was designed to evaluate the stress crack resistance (SCR) of the corrugate pipes. The SCR test method is described in FM 5-572.

1.3 The SCR test shall be performed at minimum of three different elevated temperatures in the incubation environment of water.

1.4 The SCR test data obtained from the elevated temperatures are shifted to a lower site specific temperature using the equations defined by Popelar, et al., (1991)

2. REFERENCED DOCUMENTS

2.1 ASTM Standards:

D1600 Terminology for Abbreviated Terms Relating to Plastics

D5397 Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test

E145 Standard Specification for Gravity-Convection and Forced Ventilation Ovens

F2136 Standard Test Method for Notched Constant Ligament Stress (NCLS) Test to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe

2.2 Florida Standards

FM5-572 Test Method for Determining Slow Crack Growth Resistance of HDPE Corrugated Pipes.

2.3 Other Documents:

Popelar, C.H., Kenner, V.H., and Wooster, J.P. (1991) "An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials", Polymer Engineering and Science, Vol. 31, No. 24, pp. 1693-1700.

3. STRESS CRACK RESISTANCE (SCR) TEST

3.1 The SCR test shall be performed according to FM 5-572.

3.1.1 Procedure A uses notched dumbbell shaped test specimens.

3.1.2 Procedure B uses pipe junction specimens

3.1.3 Procedure C uses specimens consist of longitudinal profiles, such as vent-hole and mold line

3.2 The SCR test shall be tested in the environment of tap water.

Note 1 – In case of dispute, the water should be distilled or deionized.

3.3 The test temperatures shall range between 60 and 80^{o}C. The test shall be carried out at three different temperatures at 10^{o}C interval between them.

Note 2 – No tests shall be performed at temperature exceed 80^{o}C

3.4 Applied stresses shall range from 200 to 600 psi. For each test temperature, minimum of three stress levels shall be tested at maximum increments of 100 psi. The applied stresses at different test temperatures are shown in Table 1.

Note 3 – Tests performed at stresses higher than the defined values may enter into the transition region of the ductile-brittle curve thereby yielding a longer failure time than that of the lower stress. Details of the ductile-brittle transition can be found in ASTM D5397.

3.5 Five specimens are tested at each stress level to produce statistically significant results.

Table 1 – Applied Stresses at Different Test Temperatures

Test Temperature (^{o}C)	Applied Stresses (psi)
60	400, 500, 600,
70	300, 400, 500
80	200, 300, 400

4. STRESS CRACK RESISTANCE TEST DATA ANALYSIS

4.1 At each of the applied stresses, calculate the arithmetic mean of the five failure times and report it as the “average failure time” for that particular applied stress.

Note 4 – It is anticipated that a large variation in the failure times would result when junction and longitudinal profiles are being tested. If one out of five specimens exhibits an abnormally short failure time, this particular failure time can be excluded from the calculation to obtain the average failure time.

4.2 The test can be terminated after reaching the durations according to the values defined in Table 2. For those specimens that have not reached brittle failure, their failure times shall be taken as the test duration.

Table 2 – Duration of the SCR test

Test Temperature (^oC)	Applied Stress (psi)	Test Duration (hour)
60	400	7000
	500	7000
	600	7000
70	300	4000
	400	4000
	500	4000
80	200	1500
	300	1500
	400	1500

4.3 Present the test data in graphic form by plotting the logarithm of applied stress versus the logarithm of the average failure time for each test temperature.

4.4 Apply the power law equation to each temperature data to obtain the best fitted curve. An example of the test results obtained from FM 5-572 test procedure A is shown in Figure 1.

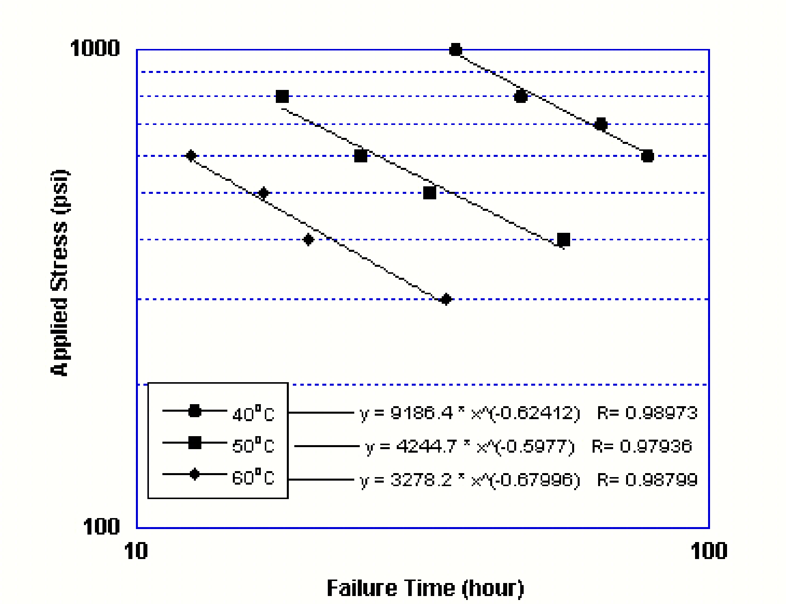


Figure 1 – An example to illustrate the results of SCR tests at three different temperatures

5. PREDICTION METHOD

5.1 The three sets of SCR data obtained from the elevated temperatures are shifted to a site specific temperature according to Equations (1) and (2) that are defined by Popelar, et al., (1991).

$$a_T = \exp[-0.109(T - T_R)] \quad (1)$$

$$b_T = \exp[0.0116(T - T_R)] \quad (2)$$

where:

a_T = *horizontal shift function (time function)*
b_T = *vertical shift function (stress function)*
T = *temperature of the test*
T_R = *target temperature (in this case this is site temperature)*

5.2 The average temperature of 20°C shall be used as the general site temperature in the lifetime extrapolation analysis.

5.3 Present all the shifted data in graphic form by plotting the logarithm of applied stress versus the logarithm of the average failure time at the site temperature.

5.4 Apply the power law equation to shifted data to obtain the best fitted curve. The resulting power law equation shall be used to predict the crack free lifetime of the pipe. Figure 2 shows an example of the shifted data with power law fitted equation. The general power law equation is shown as Equation (3).

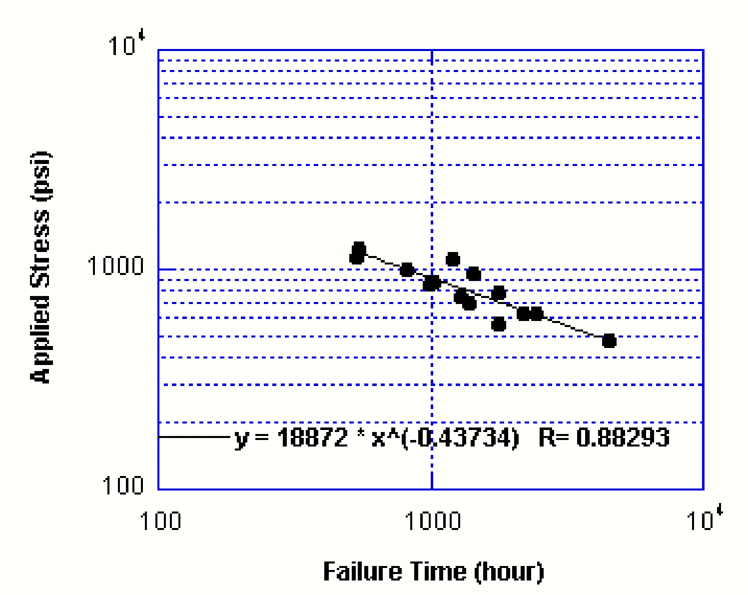


Figure 2 – An example of the shifted data using Equations (1) and (2)

$$\sigma = At^b \qquad (2)$$

Where:

σ = *Applied stress (psi)*
t = *Failure time (hr)*
A and b = *Constants*

5.5 Substitute the expected axial tensile stress (σ) that is obtained from finite element analysis using the specific site design parameters into the fitted equation to yield the failure time. The failure time shall be greater than 100 years (or 876,000 hours)

6. REPORTING RESULTS

Test report shall include the following information:

6.1 All details necessary for complete identification of the material tested (AASHTO M 294 cell class).

6.2 Test information and results shall be recorded according in the format shown in Table 3.

6.3 Report the shifted data, fitted power law equation and shifted graph.

6.4 The axial tensile stress used to calculate the failure time of the pipe during service lifetime.

Table 3 – Recommend Data Record Template

<table>
<tr><td colspan="7">Date:
Sample Identification:
Pipe Region being Evaluated:
Test Procedure:</td></tr>
<tr><td colspan="7">Test Temperature:</td></tr>
<tr><th>Applied Stress (psi)</th><th>Average Thickness (in)</th><th>Notch Depth (in)</th><th>Ligament Thickness (in)</th><th>Applied Load (lb)</th><th>Failure Time (hr)</th><th>Average Failure Time (hr)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="3"></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

APPENDIX C

Florida Method of Test for Predicting the Oxidation Resistance of HDPE Corrugated Pipes

Designation, FM 5-574

Florida Method of Test for Predicting the Oxidation Resistance of HDPE Corrugated Pipes

Designation, FM 5-574

1. SCOPE

1.1 This test method is used to predict the oxidation resistance of high density polyethylene (HDPE) corrugated pipes in view of Florida DOT 100-year design service life requirement. This protocol utilizes the oxidative induction time (OIT) test to evaluate accelerated aging pipe samples.

1.2 The aging acceleration is achieved by incubating at minimum of three different elevated temperatures in water environment.

1.3 The OIT data obtained from the elevated temperatures are extrapolated to a lower site specific temperature using the Arrhenius equations.

1.4 The mechanical properties (tensile properties) are also measured along with OIT test results to confirm the changes in the polymer during the course of incubation.

2. REFERENCED DOCUMENTS

2.1 ASTM Standards:

D1600 Terminology for Abbreviated Terms Relating to Plastics

D3895 Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry

D638 Test Method for Tensile Properties of Plastics - Type V

D5721 Air-Oven Aging of Polyolefin Geomembranes

2.2 Other Documents:

Hsuan, Y.G. and Koerner, R.M., (1998) “Antioxidant Depletion Lifetime in High Density Polyethylene Geomembranes”, Journal of Geotechnical and Geo-environmental Engineering, ASCE, Vol. 124, No. 6., pp. 532-541.

3. Incubation Procedure

3.1 Prepare minimum of 45 pipe liner samples with dimensions of 5 inch in the circumferential direction and 4 inch in the longitudinal direction.

Note 1 – The crown of the pipe shall be removed

3.2 Place 15 liner samples in each of the three hot water baths.

Note 2 – Since polyethylene is lighter than water, stainless steel metal clips shall be attached to the samples to weight them down. The samples must be separated from each other during the incubation.

3.3 The incubation shall be at three different temperatures with a 10°C interval between them. The temperatures of the three baths shall range between 55 and 85°C.

Note 3 – four different temperatures will generate greater accuracy in the extrapolation.

3.4 At 3 months and 6 months, incubated samples shall be removed for evaluation; thereafter remove an incubated sample from each of the baths in every 6-month.

3.5 The duration of the incubation is dependent on the results of three evaluated properties. For the long-term performance test, the incubation shall be carried out until there is 80% decrease in the breaking strain.

4. EVALUATION OF ORIGINAL AND INCUBATED SAMPLES

4.1 Tensile Properties

4.1.1 Five ASTM D 638-TypeV test specimens shall be die cut from the original non-incubated sample and incubated sample. The length of the specimens shall be parallel to the longitudinal direction of the pipe.

4.1.2 Perform tensile tests according to ASTM D638-TypeV, using a strain rate of 2 in/min. Record Young's modulus, yield stress, yield strain, break stress and break strain.

Note 4 – the yield strain and break strain can be obtained using cross-head movement instead of an extensometer.

4.2 OIT Test

4.2.1 Perform OIT test according to ASTM D3895, employing the following procedures

4.2.1.1 Use open aluminum pan.

4.2.1.2 A two-point temperature calibration must be performed at a minimum once per week.

4.2.1.3 Two replicates shall be tested for each test sample.

4.3 The changes in tensile properties and OIT value at each incubation interval shall be monitored by plotting these properties against incubation time until 80% decrease in breaking strain is achieved.

5. PREDICTION METHOD FOR ANTIOXIDANT LIFETIME

5.1 To perform this prediction analysis, the OIT value at the lowest incubation temperature must reach greater than 70% reduction.

5.2 Plot the average OIT value in natural log scale versus incubation time for three incubation temperatures, as shown in Figure 1.

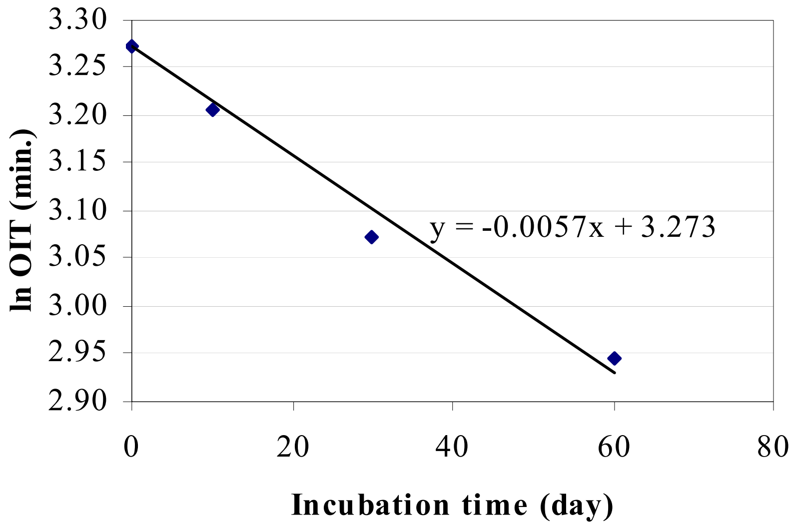

Figure 1 – OIT versus time plot

5.3 Fit the data with a linear equation but the straight line must pass the original ln(OIT) value as shown in Figure 1.

5.4 The slope of the line is the antioxidant depletion rate (S). The (S) value shall be presented in a table together with the incubation temperature, as shown in Table 1.

Table 1 – Antioxidant depletion rate at each incubation temperature

Slope (S)	Incubation Temperature (T) (^{o}C)	Incubation Temperature (T) (K)	Inverts Temperature (1/T) (1/K)

5.5 Perform Arrhenius plot by plotting ln(S) versus (1/T). A data shall be fitted with a straight line, as shown in Figure 2.

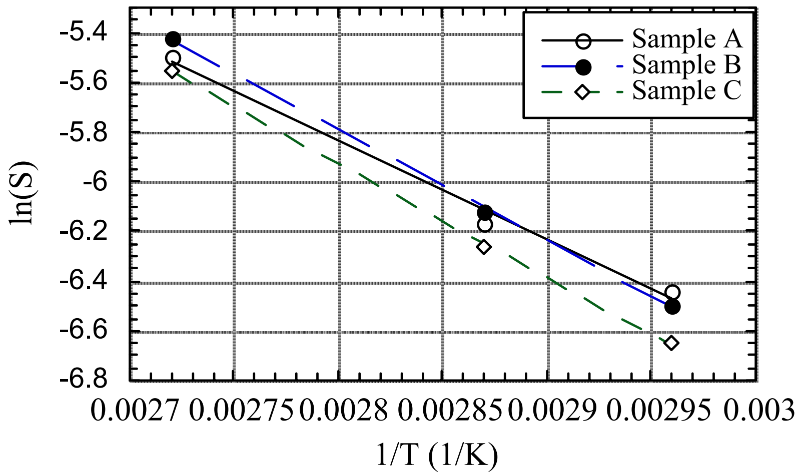

Figure 2 – Arrhenius plot of the antioxidant depletion rate versus temperature

5.6 The resulting Arrhenius equation, as shown in Equation (1), from Figure 2 shall be used to extrapolate the antioxidant depletion rate at site specific temperature.

$$S = A^{*}\exp(-E/RT) \qquad (1)$$

where:

S = OIT depletion rate
E = Activation energy of the antioxidant depletion reaction under this test condition (kJ/mol)
R = gas constant (8.31 J/mol.K)
T = test temperature in absolute Kelvin (degrees K)
A = constant

5.7 The average temperature of 20°C shall be used as the general site temperature in the lifetime extrapolation analysis.

5.8 The lifetime (t) of the antioxidants at site specific temperature shall be calculated using Equation (2).

$$OIT = P^{*} \exp(- S^{*}t) \qquad (2)$$

where:

OIT = OIT time (min.) which is 0.5 minutes.
P = original OIT of the geomembrane (min.)
S = OIT depletion rate (min/day)
t = lifetime (days)

6. PREDICTION METHOD TO DETERMINE LIFETIME OF PIPE BASED ON OXIDATION DEGRATION

6.1 To perform this analysis, the break strain shall decrease more than 80% at all three incubation temperatures.

6.2 Calculate the average break strain at each incubation interval. Determine the percent break strain retained value using Equation (3).

$$\%\ \textit{break strain retained} = \frac{\textit{average strain value at each incubation interval}}{\textit{average strain value of original sample}} \qquad (3)$$

6.3 Plot the percent break strain retained value versus incubation time for three incubation temperatures, as shown in Figure 3. From the plot, determine the time to reach 20% break strain retained (i.e., 80% drop in break strain).

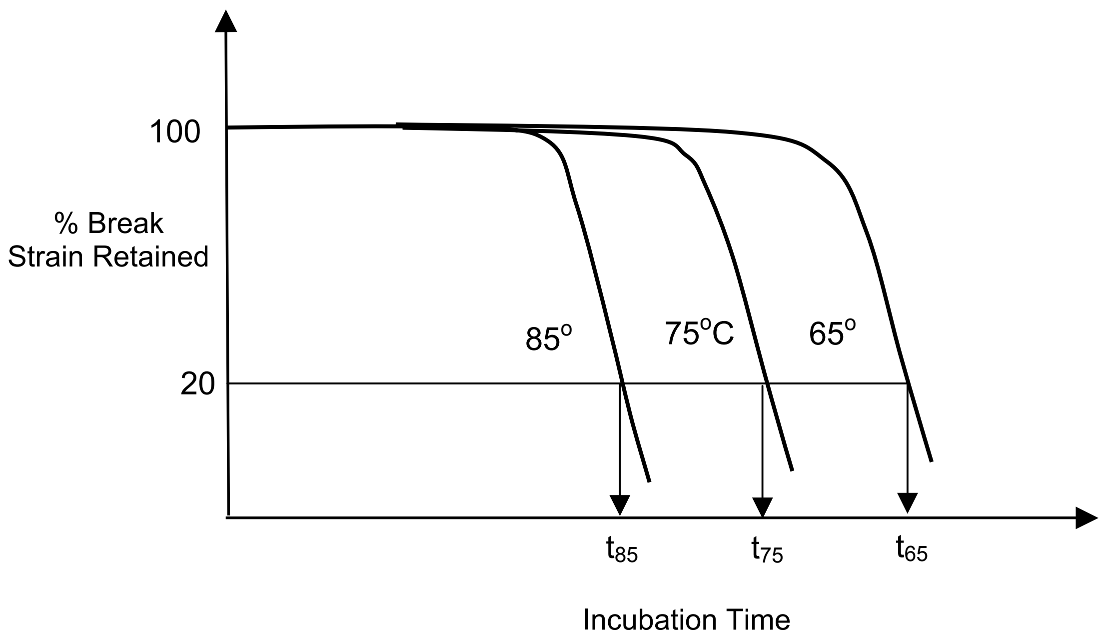

Figure 3 – Determine the time to reach 20% break strain retained

6.4 Determine the reaction rate at each incubation temperature using equation (4).

$$\textit{Reaction Rate } (R_{temperature}) = \frac{1}{t_{temperature}} \qquad (4)$$

6.5 Perform Arrhenius plot by plotting ln($R_{temperature}$) versus ($1/T$). A data shall be fitted with a straight line.

6.6 The Arrhenius equation obtained from 6.5 shall be used to extrapolate the 80% drop in break strain at site specific temperature (t_{site}) which is the lifetime of the pipe based on oxidation degradation.

7. REPORTING RESULTS

7.1 The material properties versus incubation time plot for all three incubation temperatures.

7.2 Report lifetime of antioxidant in years.

7.3 Report lifetime of the pipe based on oxidation degradation in years.

APPENDIX D

Florida Method of Test
for Determining Creep Rupture of
Corrugated Pipe Liner Tensile Specimens

Designation, FM 5-575

Florida Method of Test for
Determining Creep Rupture of
Corrugated Pipe Liner Tensile Specimens

Designation, FM 5-575

1. SCOPE

   1.1 This test method is used to determine time-to-failure of HDPE corrugated pipe liner tensile specimens under constant applied stresses.

   1.2 The test data generated on these specimens shall be analyzed according to Florida Method of Test for Predicting the Long-Term Tensile Strength of Corrugated High Density Polyethylene (HDPE) Pipes-FM 5-576.

   1.3 The values stated in inch-pound units are to be regarded as the standard. The values given in parenthesis are mathematical conversions to SI units, which are provided for information only and are not considered standard.

2. REFERENCED DOCUMENTS

   2.1 ASTM Standards:

   D1600 Terminology for Abbreviated Terms Relating to Plastics

   D 638 Test Method for Tensile Properties of Plastics

   D 2990 Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

   F2136 Standard Test Method for Notched Constant Ligament Stress (NCLS) Test to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe

   F2018 Time-to-Failure of Plastics Using Plane Strain Tensile Specimens

   2.2 Florida Standards

   FM5-576 Test Method for Predicting Long-Term Tensile Strength of HDPE Corrugated Pipes

3. TEST METHOD

   3.1 This test method consists of a description of the locations of test specimens in the liner section of the corrugated pipe and the creep rupture tests in a controlled-temperature water bath.

4. APPARATUS

4.1 Blanking Die - A die suitable for cutting test specimens to the dimensions and tolerances specified in ASTM D 638 Types IV or Type V. Type IV die shall be used for pipes with diameter from 42 to 60 inches. Type V die shall be used for pipes with diameter from 12 to 36 inches.

4.2 Creep Testing Apparatus. - A lever loading machine, with a lever arm ratio of 3:1 to 5:1 similar to that described in ASTM D 5397. Alternatively the tensile load may be applied directly using dead weights or any other method for producing a constant stress.

(Testing apparatus is available from BT Technology, Inc. 320 N. Railroad Street, Rushville, IL 62681, Materials Performance, Inc. 2151 Harvey Mitchell Pkwy, S. Suite 208, College Station, TX 77840, Satec Systems, 900 Liberty Street, Grove City, PA 16127, or equivalent.)

4.3 Micrometer (or caliper) capable of measuring to +/- 0.0005 in (+/- 0.0127 mm).

4.4 Metal shot for weight tubes.

4.5 Electronic scale for measuring shot weight tubes capable of measuring to +/- 0.0002 lbs. (0.1 g).

4.6 Timing device capable of recording failure time to the nearest 0.1 h.

5. SPECIMEN PREPARATION

5.1 Test specimens are to be die cut from the inner liner of the corrugated pipe. The specimens shall be oriented along the longitude axis of the pipe, as shown in Figure 1.

5.2 Five specimens shall be cut from same circumferential section of the test pipe but at locations of 70^{o} apart from each other.

5.3 The average thickness of each test specimen shall be determined by averaging three thickness measurements of the constant neck section.

6. CALCULATION

6.1 Calculate the stress of each test specimen as follows:

$$S = P/(W*t) \qquad (1)$$

Where:

S = applied stress (psi)
P = tensile load (lb or g)
W = width of specimen (in)
t = average thickness of the specimen (in)

6.2 Each test weight so determined is to be labeled (or otherwise correlated to each test position) and applied to the appropriate lever arm on the test apparatus.

7. PROCEDURE:

7.1 Maintain temperature in the bath at the incubation temperature, which shall be one of the four elevated temperatures: 50, 60, 70 or 80^{o}C.

7.2 Test five (5) specimens at each stress level, which ranges from 100 to 700 psi.

7.3 Determine the weight to be placed on each specimen, and load the weight tubes with shot. Do not attach the shot tube to the lever arm.

7.4 Attach the specimens to the loading frame. Take care that bending the specimen does not activate the notch. Lower the specimen into the bath, and condition the specimens in the bath for at least 60 minutes.

7.5 Reset the specimen timer to zero.

7.6 Check that the weight is the correct weight for the particular specimen, and carefully connect the weight tube to the appropriate lever arm for the specimen. Apply the load gradually within a period of 5 to 10 s without any impact on the specimen.

7.7 Start the specimen timer immediately after loading.

7.8 Record the time to failure of each specimen to the nearest 0.1 h.

8. REPORTING RESULTS

The test report shall include the following information:

8.1 Complete identification of the material tested (material type, manufacturer's name and code number).

8.2 The load placed on each lever as per equation in 6.1 and cross-sectional dimension of each specimen.

8.3 Test temperature

8.4 Report the failure time for each of the five specimens and the arithmetic average of each specimen set of five specimens.

8.5 Plot applied stress against average failure time in a log-log scale.

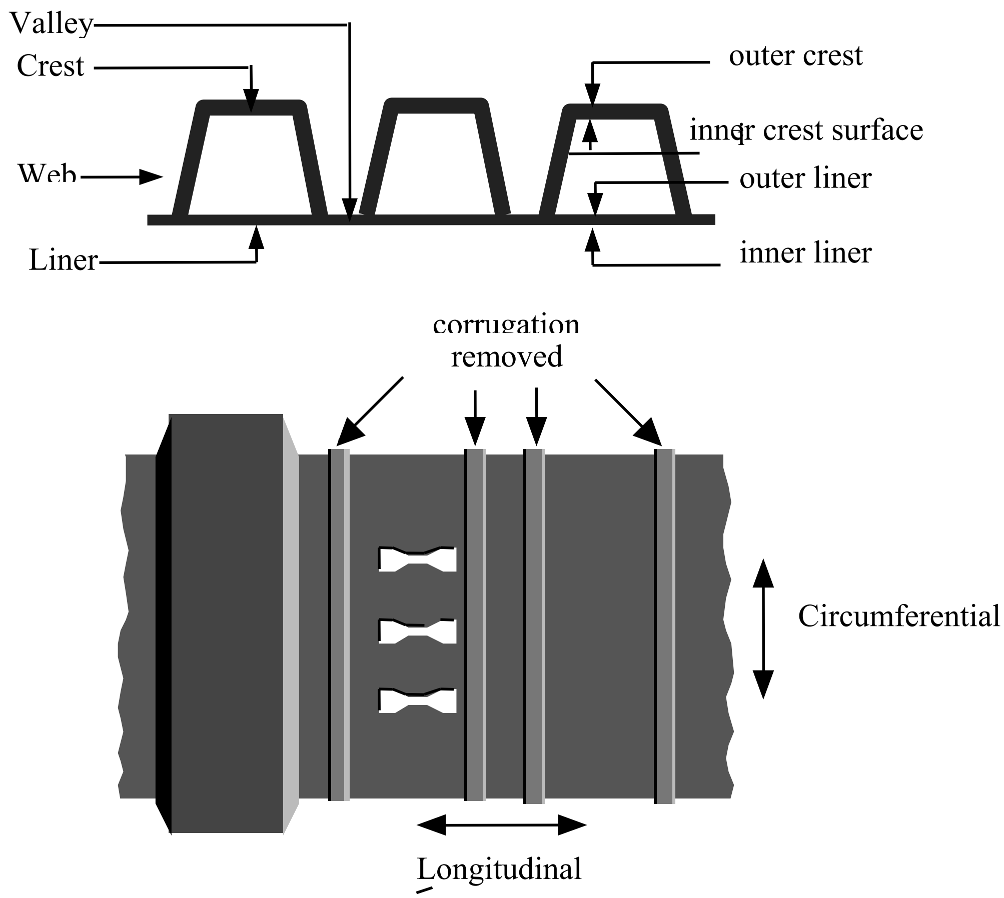

Figure 1 – Location of test specimens to evaluate tensile properties of pipe

APPENDIX E

Florida Method of Test
for Florida Method of Test
for Predicting Long-Term Tensile Strength
of HDPE Corrugated Pipes

Designation, FM 5- 576

Florida Method of Test for Predicting Long-Term Tensile Strength of HDPE Corrugated Pipes

Designation, FM 5-576

1. SCOPE

1.1 This test method is used to predict the long-term tensile strength of high density polyethylene corrugated pipes in view of Florida DOT 100-year design service life requirement.

1.2 The test utilizes creep rupture data obtained from FM 5-575 test method on pipe liner material.

1.3 The tests shall be performed at minimum of three different elevated temperatures in the incubation environment of water.

1.4 The creep rupture data obtained from the elevated temperatures are shifted to a lower site specific temperature using the equations defined by Popelar, et al., (1991)

2. REFERENCED DOCUMENTS

2.1 ASTM Standards:

D1600 Terminology for Abbreviated Terms Relating to Plastics

D 638 Standard Test Method for Tensile Properties of Plastics

D 2990 Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

F2136 Standard Test Method for Notched Constant Ligament Stress (NCLS) Test to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe

2.2 Florida Standards:

FM 5-575 Test Method for Determining Creep Rupture of HDPE Corrugated Pipes

2.3 Other Documents

Popelar, C.H., Kenner, V.H., and Wooster, J.P. (1991) “An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials”, Polymer Engineering and Science, Vol. 31, No. 24, pp. 1693-1700.

3. CREEP RUPTURE TEST

3.1 The creep rupture test shall be performed according to the FM 5-575 using ASTM D 638 Type IV or Type V specimens.

3.2 The creep tests shall be tested in the environment of tap water.

Note 1 – In case of dispute, the water should be distilled or deionized.

3.3 The test temperatures shall range between 50 and 80°C. Test shall not be performed at a temperature exceeding 80°C. The SCR test shall be carried out at three different temperatures at 10°C interval between them.

3.4 Applied stresses shall range from 100 to 800 psi. At each test temperature, a minimum of four stress levels shall be tested at maximum increments of 100 psi. The applied stresses at different test temperatures are shown in Table 1.

Note 2 – Tests performed at stresses higher than the defined values may enter into the transition region of the ductile-brittle curve, yielding a longer failure time than that of the lower stress. Details of the ductile-brittle transition can be found in ASTM D5397.

3.5 Five specimens are tested at each stress level to produce statistically significant results.

Table 1 – Applied Stresses at Different Test Temperatures

Test Temperature (°C)	Applied Stresses (psi)
50	600 to 1000,
60	500 to 900,
70	400 to 800
80	300 to 700

4. DATA ANALYSIS

4.1 For each of the applied stresses, calculate the arithmetic mean of the three failure time values and report it as the "average failure time" for that particular applied stress.

4.2 For test specimens that do not fail after 2000 hours testing time, tests shall be terminated and recorded their failure times as 2000 hours.

4.3 Present test data in graphic form by plotting the logarithm of applied stress versus the logarithm of the average failure time for each test temperature. An example of the results is shown in Figure 1.

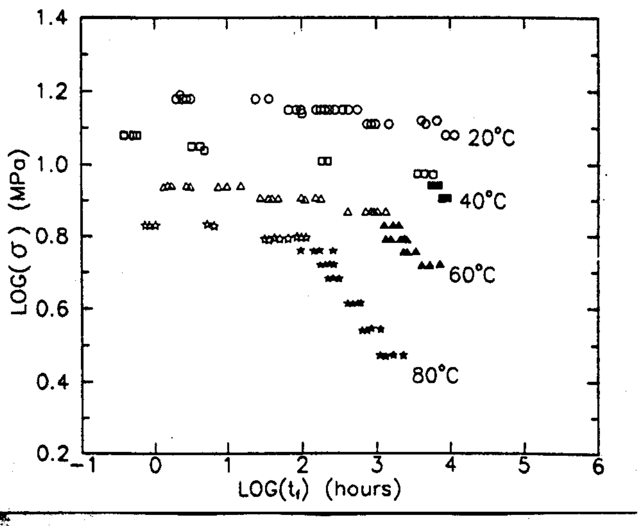

Figure 1 – An example to illustrate the results of SCR tests at three different temperatures (ref. Popelar, et al., 1991)

5. PREDICTION METHOD

5.1 The three sets of creep rupture data obtained from the elevated temperatures are shifted to a site specific temperature according to Equations (1) and (2) that are defined by Popelar, et al., (1991).

$$a_T = \exp[-0.109(T - T_R)] \quad (1)$$

$$b_T = \exp[0.0116(T - T_R)] \quad (2)$$

where:

a_T = *horizontal shift function (time function)*
b_T = *vertical shift function (stress function)*
T = *temperature of the test*
T_R = *target temperature (in this case this is site temperature)*

5.2 The average temperature of 20°C shall be used as the general site temperature in the lifetime extrapolation analysis.

5.3 Present all the shifted data in graphic form by plotting the logarithm of applied stress versus the logarithm of the average failure time at the site temperature. Figure 2 shows an example of the shifted data.

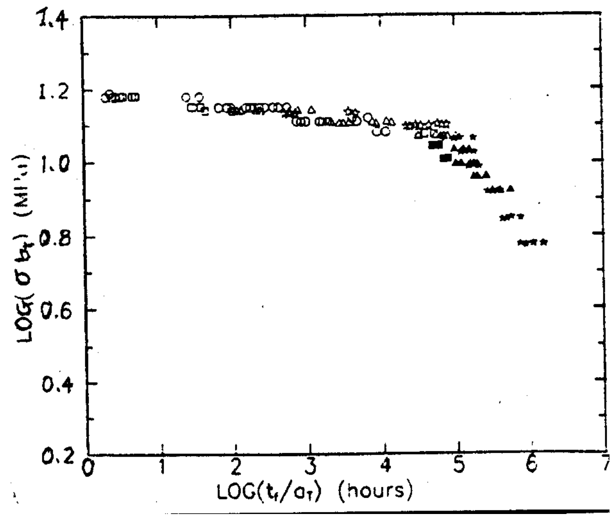

Figure 2 – An example of the shifted data from Figure 1

5.4 Apply power law equation to shifted data to obtain the best fitted curve. The resulting power law equation shall be used to predict the long-term tensile strength of the pipe. The general power law equation is shown as Equation (3).

$$\sigma = At^b \tag{3}$$

Where:

σ = Applied stress (psi)
t = Failure time (hr)
A and b = Constants

5.5 Substitute the expected axial tensile stress (σ) that is obtained from finite element analysis using the specific site design parameters into fitted equation to yield the failure time. The failure time shall be greater than 100 years (or 876,000 hours)

6. REPORTING RESULTS

The test report shall include the following information:

6.1 All details necessary for complete identification of the material tested (AASHTO M 294 cell class).

6.2 Test information and results shall be recorded according in the format shown in Table 2.

6.3 Report the shifted data, fitted power law equation and shifted graph.

6.4 The axial tensile stress used to calculate the failure time of the pipe during service lifetime.

Table 2 – Recommend Data Record Template

Applied Stress (psi)	Average Thickness (in)	Applied Load (lb)	Failure Time (hr)	Average Failure Time (hr)

APPENDIX F

Florida Method of Test for Predicting Long-Term Flexural Modulus of HDPE Corrugated Pipes

Designation, FM 5-577

Florida Method of Test for
Predicting Long-Term Flexural Modulus
of HDPE Corrugated Pipes

Designation, FM 5-577

1. SCOPE

1.1 This test method is used to predict the long-term flexural modulus of high density polyethylene corrugated pipes in view of Florida DOT 100-year design service life requirement.

1.2 The test utilizes stress relaxation data obtained from ASTM D2412 test method on corrugated pipes with diameter less than 24 inches.

1.3 The tests shall be performed at minimum of six elevated temperatures in the incubation environment of air.

1.4 The stress relaxation data obtained from the elevated temperatures are shifted to a lower site specific temperature using the equations defined by Popelar, et al., (1991)

2. REFERENCED DOCUMENTS

2.2 ASTM Standards:

D1600 Terminology for Abbreviated Terms Relating to Plastics

D 2412 Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading

2.2 Other Documents:

Popelar, C.H., Kenner, V.H., and Wooster, J.P. (1991) "An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials", Polymer Engineering and Science, Vol. 31, No. 24, pp. 1693-1700.

Selig, E.T (1995), "Long-Term Performance of Polyethylene Pipe under High Fill", Geotechnical Report No. PDT95-424F, Technical Report – Part 2, Research Project No. 88-14, Pennsylvania Department of Transportation, Harrisburg, PA.

3. STRESS RELAXATION TEST

3.1 The stress relaxation test shall be performed based on ASTM D 2412 procedure with modifications as follows:

3.1.1 Compress the pipe specimen at a constant rate of 0.5 in/min until deflection reaches 5% of the average inside diameter of specimen.

Note 1 – The test apparatus can be simple metal frame equipment with a load cell that has the appropriate capacity to measure the changing load with time. Figure 1 is a test apparatus that was used by Selig (1995) for stress relaxation test on 24 inch corrugated pipes.

3.1.2 Hold the pipe at 5% deflection and monitor load changes with time.

3.1.3 Terminate the test after 24 hours.

Note 2 – the testing time may need to extend to a longer hour depending on the resulting Master curve at 20°C after shifting. The duration of the Master curve shall not be shorter than 10-years from which a 100-year modulus can be extrapolated.

3.2 The stress relaxation tests shall be tested in the environment of air at five elevated temperatures, ranging from 35 to 85°C at 10°C intervals.

3.4 Each test temperature shall be held at an accuracy of ±2°C.

Note 3 – The temperature chamber can be made from extruded polystyrene foam panels and are placed around the test pipe. The elevated temperatures can be achieved by forcing hot air into the incubation chamber.

4. DATA ANALYSIS

4.1 At each test temperature, the load changes with time shall be recorded for duration of 1000 hours.

4.2 The pipe stiffness, PS, shall be calculated according to the equation (1) which is defined in ASTM D 2412.

$$PS = \frac{F}{\Delta y}\left(1 + \frac{\Delta y}{2d}\right)^3 \tag{1}$$

where: F = applied load per unit length (lb/in)
Δy = inside vertical diameter change (in), and
d = initial inside vertical diameter

4.3 The flexural modulus of the pipe at 5% deflection shall be calculated using equation (2) which is defined in ASTM D 2412.

$$E = \frac{0.149 r^3 (PS)}{I} \tag{2}$$

where: E = flexural modulus
r = half the sum of the inner diameter and one corrugation depth
I = bending moment

4.4 Present test data in graphic form by plotting the logarithm of flexural modulus versus the logarithm of the testing time for each temperature. An example of the results is shown in Figure 2.

4.5 The five sets of stress relaxation data obtained from the elevated temperatures are shifted to a 25°C temperature according to Equations (3) and (4) that are defined by Popelar, et al., (1991), yielding a master curve at 20°C. An example of the results is shown in Figure 3.

$$a_T = \exp[-0.109(T - T_R)] \tag{3}$$

$$b_T = \exp[0.0116(T - T_R)] \tag{4}$$

where:

a_T = *horizontal shift function (time function)*
b_T = *vertical shift function (stress function)*
T = *temperature of the test*
T_R = *target temperature (in this case this is site temperature)*

4.6 The duration of the resulting master curve must be longer than 10-year. If the duration of the master curve is shorter than 10-year, a new set of stress relaxation tests shall be performed by extending the individual testing time from 24 hours to 48 hours.

4.7 The master curve at 20°C shall be fitted with a power law equation, as displaced in Figure 3, from which the 100 year modulus value can be predicted.

5. REPORTING RESULTS

Test report shall include the following information:

5.1 All details necessary for complete identification of the material tested (AASHTO M 294 cell class).

5.2 Test temperatures and modulus versus time curve at each temperature.

5.3 Report the shifted data, fitted power law equation and shifted graph with master curve.

5.4 Report predicted modulus value at 100-year using the power law equation.

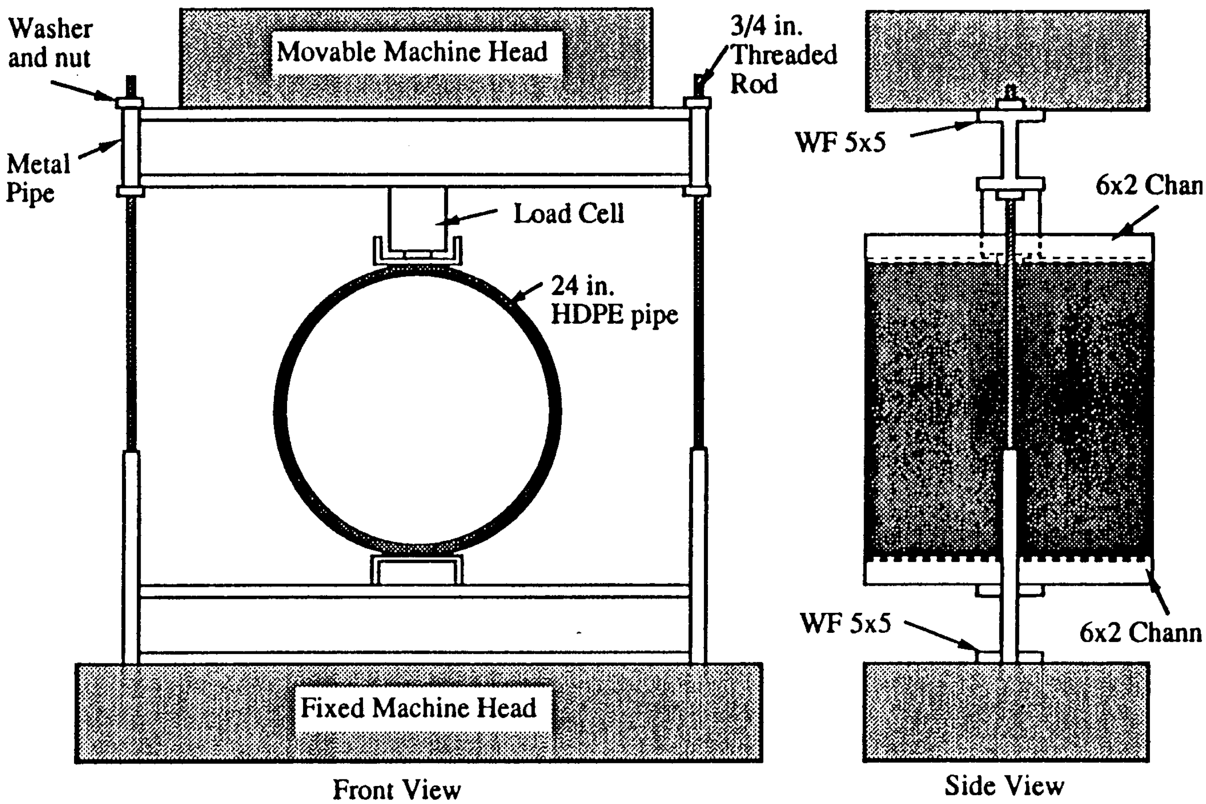

Figure 1 – Parallel Plate test set up for stress relaxation test of corrugated pipe, (Selig, 1995)

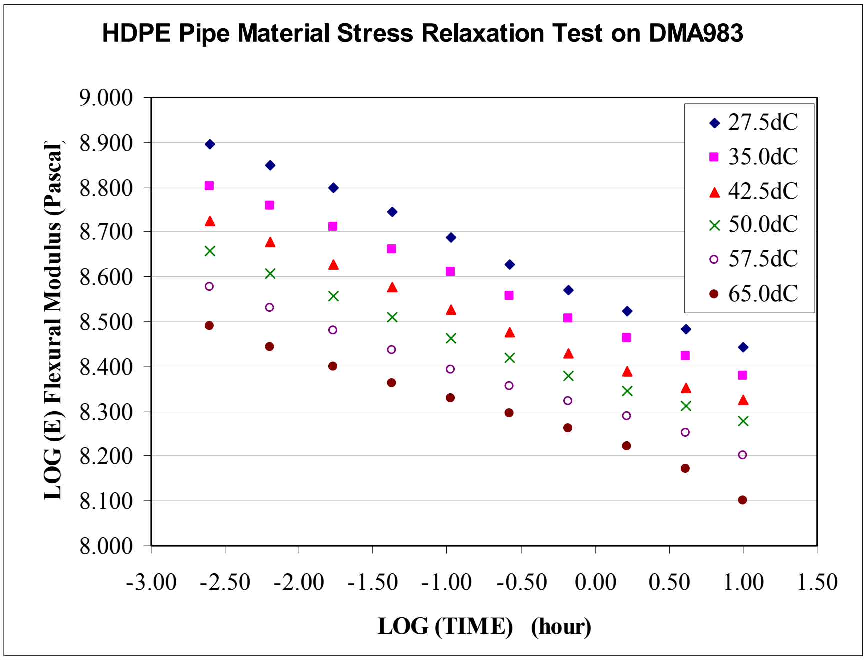

Figure 2 - Stress relaxation curves resulted from the DMA test-1

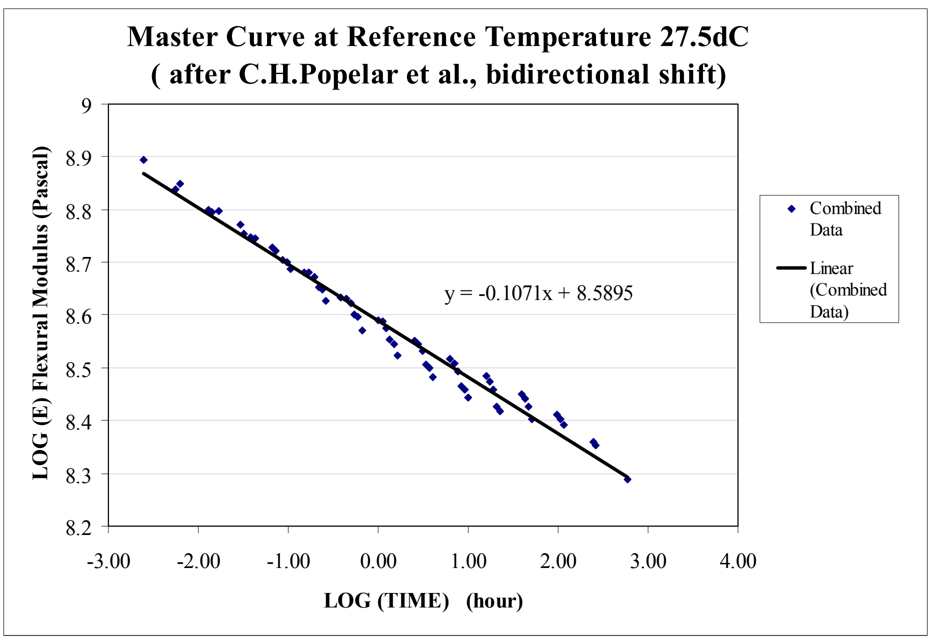

Figure 3 - Master curve at 27.5 after shifted using Popelar factors

APPENDIX G

NCLS TEST DATA

Sample - P-1 Compression Plaque						
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position M-3**	**K Value (psi/√in)**	**Failure Time (hours)**
600	**0.073**	**0.059**	**669**	**11**	**137.74**	**16.7**
	0.073	**0.059**	**669**	**12**	**137.74**	**18.1**
	0.073	**0.059**	**669**	**13**	**137.74**	**19.1**
	0.074	**0.060**	**680**	**14**	**137.58**	**16.4**
	0.075	**0.061**	**692**	**15**	**137.43**	**18.8**
				Average Failure Time		**17.8**
				Standard Diviation		**1.2**

Sample - P-1 Pipe Liner						
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position M-1**	**K Value (psi/√in)**	**Failure Time (hours)**
600	**0.078**	**0.064**	**0**	**16**	**137.02**	**12.3**
	0.080	**0.066**	**0**	**17**	**136.77**	**13.2**
	0.081	**0.067**	**0**	**18**	**136.66**	**15.2**
	0.082	**0.068**	**0**	**19**	**136.54**	**10.9**
	0.085	**0.071**	**0**	**20**	**136.24**	**11.3**
				Average Failure Time		**12.6**
				Standard Deviation		**1.7**

Sample - P-1 Pipe Liner Condition - 10% Igepal at 50°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
400	0.080	0.066	499	11	26.7
400	0.080	0.066	499	12	39.5
600	0.081	0.067	760	15	11.6
600	0.081	0.067	760	16	12.6
800	0.081	0.067	1013	17	9.1
800	0.081	0.067	1013	18	9.3
1000	0.082	0.068	1285	19	6.8
1000	0.083	0.069	1304	20	7.0

Sample - P-1 Pipe Liner Condition - Water at 40°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
600	0.078	0.064	726	13	91.2
600	0.080	0.066	748	14	64.9
700	0.080	0.066	873	15	66.9
700	0.081	0.067	886	16	62.7
800	0.081	0.067	1013	17	47.5
800	0.082	0.068	1028	18	46.3
1000	0.082	0.068	1285	19	33.8
1000	0.083	0.069	1304	17	38.1

Sample - P-1 Pipe Liner Condition - Water at 50^{o}C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
400	**0.084**	**0.070**	**529**	**1**	**50.2**
400	**0.084**	**0.070**	**529**	**2**	**61.4**
500	**0.080**	**0.066**	**624**	**9**	**32.6**
500	**0.080**	**0.066**	**624**	**10**	**32.5**
600	**0.080**	**0.066**	**748**	**7**	**25.9**
600	**0.080**	**0.066**	**748**	**8**	**23.2**
800	**0.084**	**0.070**	**1058**	**3**	**17.9**
800	**0.084**	**0.070**	**1058**	**4**	**18.1**

Sample - P-1 Pipe Liner Condition - Water at 60^{o}C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
300	**0.085**	**0.071**	**403**	**1**	**44.2**
300	**0.085**	**0.071**	**403**	**2**	**32.7**
300	**0.074**	**0.060**	**340**	**1**	**30.4**
300	**0.074**	**0.060**	**340**	**2**	**31.9**
400	**0.082**	**0.068**	**514**	**1**	**19.7**
400	**0.083**	**0.069**	**522**	**2**	**19.1**
400	**0.074**	**0.060**	**454**	**1**	**20.1**
400	**0.074**	**0.060**	**454**	**2**	**20.8**
500	**0.074**	**0.060**	**567**	**3**	**16.6**
500	**0.075**	**0.061**	**576**	**4**	**16.8**
600	**0.088**	**0.074**	**839**	**3**	**12.4**
600	**0.089**	**0.075**	**851**	**4**	**11.8**
600	**0.075**	**0.061**	**692**	**5**	**12.3**
600	**0.076**	**0.062**	**703**	**6**	**13**

Sample - P-1 Pipe Liner Condition - Air at 50°C					
Applied Stress (psi)	Thickness (in)	Ligament Thickness (in)	Applied Load (g)	Position	Failure Time (hr.)
400	0.083	0.069	391.2	5	413.8
500	0.082	0.068	482.0	4	183.97
600	0.082	0.068	578.3	3	99.25
700	0.081	0.067	664.8	2	55.39

Sample - P-1 Pipe Liner Condition - Air at 60°C					
Applied Stress (psi)	Thickness (in)	Ligament Thickness (in)	Applied Load (g)	Position	Failure Time (hr.)
400	0.082	0.068	385.6	5	155.5
500	0.078	0.064	453.6	4	64.2
600	0.078	0.064	453.6	1	27.1
600	0.078	0.064	0.0	2	34.5
600	0.082	0.068	482.0	3	25.3
600	0.084	0.070	496.1	4	24.6
600	0.085	0.071	503.2	5	24.4

Sample - P-1 Pipe Liner Condition - Air at 70°C					
Applied Stress (psi)	Thickness (in)	Ligament Thickness (in)	Applied Load (g)	Position	Failure Time (hr.)
200	0.082	0.068	257.0	5	272.11
300	0.081	0.067	379.9	3	42.47
400	0.080	0.066	499.0	2	19.48
500	0.080	0.066	623.7	1	10.94

Sample - P-1 Pipe Junction Condition - 10% Igepal at 50°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
600	**0.083**	**0.083**	**1860**	**7**	**1238.0**
	0.095	**0.095**	**2129**	**8**	**NF**
	0.084	**0.084**	**1871**	**9**	**NF**
	0.081	**0.081**	**1815**	**10**	**NF**
	0.086	**0.086**	**1927**	**11**	**207.2**
				Average Failure Time	**722.6**

NF - not failure at 1500 hour

Sample - P-1 Longitudinal Profile Condition - 10% Igepal at 50°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
500	**0.150**	**0.150**	**2801**	**11**	**NF**
	0.133	**0.133**	**2484**	**12**	**855.7**
	0.152	**0.152**	**2838**	**14**	**176**
	0.158	**0.158**	**2950**	**16**	**783.8**
	0.132	**0.132**	**2465**	**17**	**NF**
				Average Failure Time	**605.2**

NF - not failure at 1200 hours

Sample - P-2 Compression Plaque Condition - 10% Igepal at 50^{o}C						
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**K Value psi/√in**	**Failure Time (hours)**
600	0.075	0.060	680	1	143.11	20.1
	0.075	0.060	680	2	143.11	19.6
	0.075	0.060	680	3	143.11	19.3
	0.075	0.060	680	4	143.11	19.3
	0.077	0.062	703	5	142.77	20.8
-	-			Average Failure Time		19.8
				Standard Deviation		0.6

Sample - P-2 Pipe Liner Condition - 10% Igepal at 50^{o}C						
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position M-3**	**K Value psi/√in**	**Failure Time (hours)**
600	0.086	0.071	805	11	141.54	19.4
	0.088	0.073	828	12	141.32	19.8
	0.088	0.073	828	13	141.32	19.8
	0.090	0.075	851	14	141.12	19.3
	0.091	0.076	862	15	141.03	19.4
				Average Failure Time		19.5
				Standard Deviation		0.2

Sample - P-2 Pipe Liner Condition - 10% Igepal at 50^oC					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
400	0.097	0.082	620	1	44.9
400	0.098	0.083	627	2	38.6
500	0.098	0.083	784	3	28.2
500	0.101	0.086	813	4	26.4
600	0.101	0.086	975	5	20.5
600	0.102	0.087	987	6	21.4
800	0.103	0.088	1331	7	11.1
800	0.104	0.089	1346	8	11.6
1000	0.105	0.090	1701	9	9.9
1000	0.105	0.090	1701	10	7.1
1300	0.092	0.077	1892	9	6.2
1300	0.090	0.075	1843	10	5.2
1500	0.090	0.075	2126	11	1.5
1500	0.087	0.072	2041	12	1.9
1600	0.091	0.076	2298	13	0.4
1600	0.091	0.076	2298	14	0.4
1700	0.090	0.075	2410	15	0.1
1700	0.094	0.079	2538	16	0.1

Sample - P-2 Pipe Liner Condition - Water at 40°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
500	**0.098**	**0.083**	**784**	**11**	**248.7**
500	**0.101**	**0.086**	**813**	**12**	**245.7**
600	**0.102**	**0.087**	**987**	**13**	**144.8**
600	**0.102**	**0.087**	**987**	**14**	**144.7**
700	**0.103**	**0.088**	**1164**	**15**	**110.9**
700	**0.104**	**0.089**	**1177**	**16**	**119.5**
800	**0.106**	**0.091**	**1376**	**17**	**89.5**
800	**0.108**	**0.093**	**1406**	**18**	**93.6**

Sample - P-2 Pipe Liner Condition - Water at 50°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
400	**0.087**	**0.072**	**544**	**11**	**64.6**
400	**0.088**	**0.073**	**552**	**12**	**71.1**
500	**0.110**	**0.095**	**898**	**13**	**56.2**
500	**0.110**	**0.095**	**898**	**14**	**48.7**
600	**0.111**	**0.096**	**1089**	**19**	**37.2**
600	**0.113**	**0.098**	**1111**	**20**	**38.2**
800	**0.090**	**0.075**	**1134**	**13**	**19.7**
800	**0.094**	**0.079**	**1194**	**14**	**20.6**

Sample - P-2 Pipe Liner Condition - Water at 60°C					
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Failure Time (hours)**
300	**0.106**	**0.091**	**516**	**11**	**63.3**
300	**0.106**	**0.091**	**516**	**12**	**53.4**
400	**0.108**	**0.093**	**703**	**13**	**31.5**
400	**0.108**	**0.093**	**703**	**14**	**30.8**
500	**0.108**	**0.093**	**879**	**15**	**23.7**
500	**0.110**	**0.095**	**898**	**16**	**21.9**
600	**0.111**	**0.096**	**1089**	**17**	**18.2**
600	**0.113**	**0.098**	**1111**	**18**	**18.8**

Sample - P-2 Junction (side one) Condition - 10% Igepal at 50°C						
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Junction Side**	**Failure Time (hours)**
	0.102	**0.102**	**2286**	**13**	**1**	**52.9**
	0.095	**0.095**	**2129**	**14**	**1**	**83.1**
600	**0.107**	**0.107**	**2398**	**12**	**1**	**58.5**
	0.093	**0.093**	**2084**	**16**	**1**	**69.1**
	0.102	**0.102**	**2286**	**17**	**1**	**101.9**
	0.112	**0.112**	**2510**	**14**	**1**	**37.4**
	0.116	**0.116**	**2599**	**17**	**1**	**31.1**
				Average Failure Time		**62.0**
				Standard Deviation		**28.2**
Applied Stress (psi)	**Average Thickness (inches)**	**Ligament Thickness (inches)**	**Applied Load (grams)**	**Position**	**Junction Side**	**Failure Time (hours)**
	0.092	**0.092**	**2062**	**15**	**2**	**1120**
600	**0.116**	**0.116**	**2599**	**13**	**2**	**882**
	0.120	**0.120**	**2689**	**16**	**2**	*286.7**
	0.106	**0.106**	**2375**	**18**	**2**	**1030.2**

*** Specimen failed at the gripping hole**

APPENDIX H

Tensile Properties Measured by ASTM D 638 Type IV and Type V Tests

Test Material: P-1

Compression Plaque - ASTM D638-Type IV				
Sample	Yield Stress	Yield Elongation	Break Stress	Break Elongation
1	4019	14.0	2358	75
2	4091	13.8	2379	200
3	3992	13.9	391	60
4	4081	13.6	2382	107
5	4032	13.1	2282	158
Average	**4043**	**13.7**	**1958**	**120**
Note: Gauge length = 1.3 inch				

Compression Plaque - ASTM D638-Type V at strain rate of 2 in/min				
Sample	Yield Stress	Yield Elongation	Break Stress	Break Elongation
1	4101	22.2	450.4	587.8
2	4151	22.9	570.7	312.7
3	4171	22.4	1756	649
4	4192	22.0	1733	466.5
5	4158	21.7	871	660.7
Average	**4155**	**22.3**	**1076**	**535**
Note: Gauge length = 0.3 inch				

Pipe Liner longitudinal - ASTM D638-Type V at strain rate of 2 in/min				
Sample	Yield Stress	Yield Elongation	Break Stress	Break Elongation
1	3539	23.6	3948	1817
2	3656	22.9	2610	1410
3	3603	22.9	1277	1142
4	3686	23.4	2616	1689
5	3643	22.6	2671	1795
Average	**3625**	**23.1**	**2624**	**1571**
Note: Gauge length = 0.3 inch				

Ratio V/IV	**1.03**

Test Material: P-2

Compression Plaque - ASTM D638-Type IV				
Sample	Yield Stress	Yield Elongation	Break Stress	Break Elongation
1	3751	13.91	560.5	699
2	3697	13.51	401.1	421
3	3775	13.82	406.4	455
4	3633	13.92	443.7	597
5	3587	13.85	565.2	691
Average	**3688**	**13.8**	**475.4**	**572.6**
Note: Gauge length = 1.3 inch				

Compression Plaque - ASTM D638-Type V at strain rate of 2 in/min				
Sample	Yield Stress	Yield Elongation	Break Stress	Break Elongation
1	3863	23.75	2066	1579
2	3849	23.24	2156	1506
3	3805	23.57	3503	1732
4	3915	22.01	2052	1581
5	3903	24.06	1756	1205
Average	**3867**	**23.33**	**2306**	**1520**
Note: Gauge length = 0.3 inch				

Pipe Liner longitudinal - ASTM D638-Type V at strain rate of 2 in/min				
Sample	Yield Stress	Yield Elongation	Break Stress	Break Elongation
1	3594	24.79	5007	2375
2	3569	26.24	5193	2465
3	3585	24.67	2358	1550
4	3529	26.3	5249	2503
5	3613	25.39	5483	2600
Average	**3578**	**23.33**	**4658**	**2299**
Note: Gauge length = 0.3 inch				

Ratio V/IV	**1.05**

APPENDIX I

A Summary Discussion on the

Interim Specification for 100-Year Service Life of High Density Polyethylene Corrugated Pipes

A Summary Discussion on the Interim Materials Specification for 100-year Service Life of Corrugated High Density Polyethylene Pipes

Introduction

Due to the length of time required to fulfill the formal testing protocol, the Department is creating an interim materials specification, discussed below. The interim specification is based on specifications from polyethylene products used in other applications for the OIT requirement and reductions on the number and length of testing for stress crack resistance. Interim 100-year service life recognition will be given on the basis of successfully completing the interim protocol and will be granted for a two-year period during which the manufacturer is expected to complete the full testing protocol. The Department's State Materials Office may extend the interim protocol acceptance if the manufacturer has shown good faith effort but has not completed the full protocol two years after the interim acceptance is granted. Interim approval will not be considered until all interim requirements are met and all tests under the full materials specification are initiated.

Interim Specification Requirements

Table 1 shows the details of the interim specification. The interim specification targets two major properties of the pipe: stress crack resistance (SCR) and antioxidants content. All tests are performed on the finished pipe.

Technical Information

This section of the document contains technical information that was used to determine the required values in the specification. The specified values are determined based on analyses of data from published papers on other polyethylene products, such as pressured pipes and geomembranes.

Stress Crack Resistance

Part II of the test protocol demonstrates that stress cracking data obtained from the Notched Constant Ligament Stress (NCLS) test on pipe liners at elevated temperatures were successfully shifted to form a master curve at 20^{o}C site temperature using Popelar shift factors. The NCLS test is an appropriate quality control test for assessing stress cracking of the finished pipe material. An extensive research study is currently being performed by the two PIs under NCHRP project 4-26. The recommendations of the study will be adopted into the interim specification.

However, the NCLS test at present form is not suitable for 100-year crack free prediction of corrugated pipe. The 20% notch depth creates an unrealistic high stress concentration at the crack tip. The alternative approach to evaluate stress crack resistance of the finished pipes is to challenge locations that are known to be susceptible to cracking due to stress concentration. These locations are junctions and longitudinal profiles. Test specimens should be taken from those locations and then subjected to a constant applied stress for a defined length of time. The magnitude of the applied stress and the duration of the test are determined utilizing the Popelar shift factors (Popelar, et al. 1991), as described below:

From the stress analysis presented in Part I of the test protocol, the long term tensile stress in both longitudinal and circumferential directions of the corrugated pipe is 500 psi after adding a factor of safety of 1.5. This means that the corrugated pipe should not exhibit brittle cracking under 500 psi for 100-year.

The maximum temperature that can accelerate the stress cracking of HDPE material is 80°C without significantly affecting the microstructure of the material. Thus, the test temperature for the SCR test is defined at 80°C in the specification. In addition, water is used to simulate the actual site condition instead of using acceleration agent, such as 10% Igepal solution.

By applying Popelar shift factor backward to obtain applied stress and failure time at 80°C based on 500 psi and 100 year at 20°C.

$a_T = \exp[-0.109\ (T-T_R)]$ for time shift

$b_T = \exp[0.0116\ (T-T_R)]$ for stress shift

$T - T_R = (80 - 20) = 60$

$a_T = \exp[-0.109\ (60)] = \underline{0.00144}$

$b_T = \exp[0.0116\ (60)] = \underline{2.006}$

Apply shifting from 20 to 80°C:

Stress:

$$\begin{aligned} \sigma_{20} &= \sigma_{80} * b_T \\ \sigma_{80} &= \sigma_{20}/b_T \\ &= 500\text{ psi}/2.006 \\ &= \mathbf{250\ psi} \end{aligned}$$

Failure Time:

$$\begin{aligned} t_{20} &= t_{80}/a_T \\ t_{80} &= t_{20} * a_T \\ &= 100\text{ yr} * 0.00144 \\ &= 876{,}000\text{ hr} * 0.00144 \\ &= 1261\text{ hours} \\ &\approx \mathbf{1260\ hours} \end{aligned}$$

The detailed test procedure is described in Florida Test Method, FM5-572. For junction and longitudinal profiles, Procedures B and C should be used, respectively.

Antioxidants Content

The importance of antioxidants in the corrugated HDPE pipes is described in Part II of the test protocol. An appropriate amount of the antioxidants must be added to the pipe to prevent oxidation degradation. Oxidation induction time (OIT) test was selected to assess the amount of the antioxidants in the pipes, since the same test was utilized in many published studies to evaluate the depletion of antioxidants in HDPE products.

The initial OIT value required in the interim specification is based on a long-term geomembrane study (Hsuan and Koerner (1998)). The study found that the lifetime of an antioxidant package that exhibited 80 minutes of OIT value was extrapolated to be 200 years at 20^{o}C, as shown as blue line in Figure 1. However, the experimental design of the incubation chamber was to simulate HDPE geomembrane in landfill liner application, as shown in Figure 2. The geomembrane was exposed to water saturated soil on the top and dry soil underneath. The oxygen in the incubation chamber was very limited. Consequently, the depletion rate of antioxidants was very slow. This incubation design **does not simulate** the site condition of corrugated pipes that are exposed to saturated soil on the outside and water inside.

The depletion of antioxidants in water is known to be faster than in air and certainly much faster than in soil environment. In Figure 1, the red line represents the depletion of the same antioxidant package in water (published in GRI report #16). The lifetime of the antioxidant was found to be 60 years at 20^{o}C. For HDPE pipe field condition that consists of saturated soil outside and water inside, the average of the lifetime of 200 and 60 years is used and it is 130 years. The green line in Figure 1 represents the soil/water environment. The equation is expressed by Equation (1)

$$OIT = 80*\exp(-0.039t) \qquad (1)$$

To determine the OIT value that yields 100 year lifetime under the same condition as the green line, the slope of the line should be the same. The new line (black color) is expressed by Equation (2) and the new initial OIT value is calculated.

$$0.5 = A * \exp(-0.039*100) \qquad (2)$$

$$\underline{\mathbf{A = 24.7\ minutes}} \qquad (3)$$

From the above analysis, the tentative OIT value for HDPE corrugated pipes should be 25 minutes. It should be recognized that this OIT value is based on lifetime of antioxidants rather than the lifetime of the pipes; thus, it is relatively conservative.

Antioxidant Depletion Rate

It is important to note that the OIT test cannot identify the type of antioxidants. Relying solely on the OIT values to judge the longevity of different HDPE pipes can be misleading. For example, an HDPE pipe that contains a high amount of phosphite antioxidant yields a longer OIT test value than a pipe that contains a high amount of hindered phenol even though the hindered phenol has greater oxidation stability. However, the OIT test is highly suitable to monitor the depletion of antioxidants with time of an HDPE product. In order to assess the oxidation stability of HDPE pipes with different antioxidant formulations, an incubation test coupling with OIT test is required, since the antioxidant depletion rate is formula dependent. Antioxidants in the HDPE product gradually depleted in the incubation environment (either water or air) and OIT tests are performed on the incubated sample at certain time intervals to determine the depletion rate.

In the interim specification, the antioxidant depletion rate is determined based on incubation in a water bath at 85^{o}C. The duration of the incubation is 90 days. The percent retained after 90 days of incubation is currently being determined in an 85°C water incubation test being performed on the two test pipes. The OIT depletion rate will be monitored every 30 days for 90 days duration. Results are expected in December 2003. The resulting percentage retained of OIT will be adopted in the interim specification.

REFERENCES

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Popelar, C.H., Kenner, V.H. and Wooster, J.P. (1991), "An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials", Polymer Engineering and Science, Vol. 31, No. 24, pp. 1693-1700.

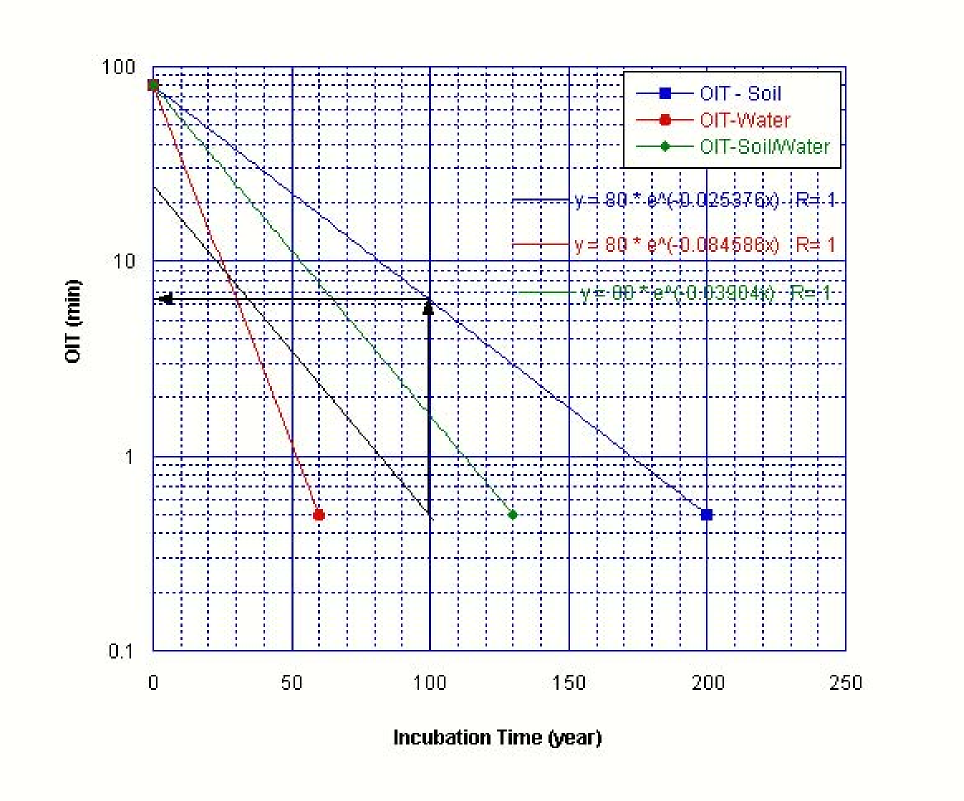

Figure 1 – The depletion of OIT versus incubation time

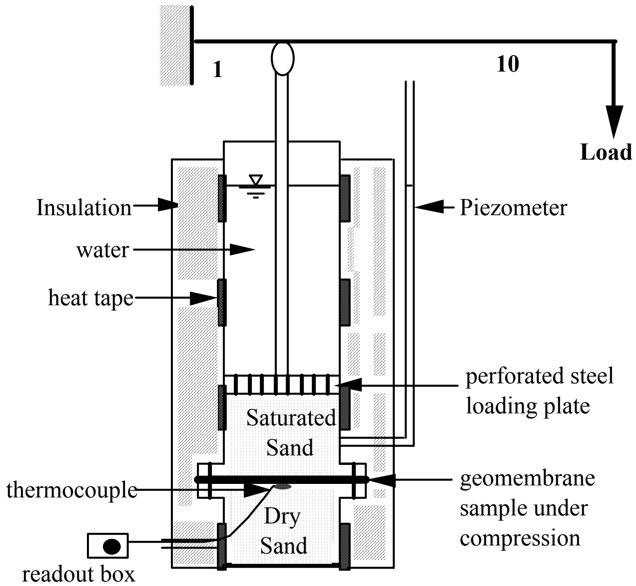

Figure 2 – Incubation chamber design for HDPE geomembrane aging study

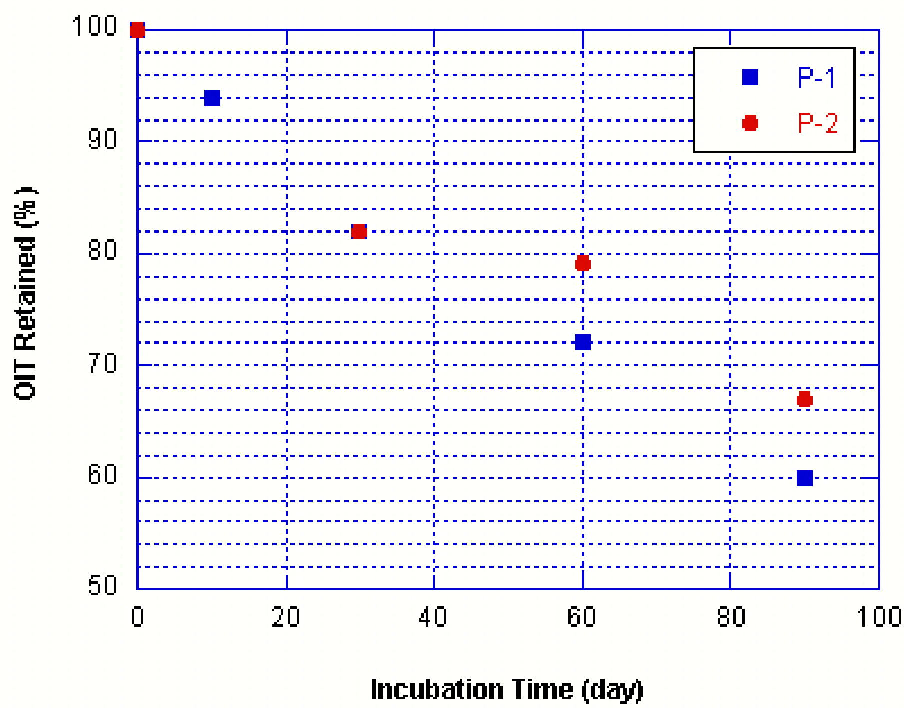

Figure 3 – Changes in percent OIT retained with incubation time of pipes P-1 and P-2

Table 1 – Interim Specification for 100-year Design Life of Corrugated HDPE Pipe

Pipe Location	Test Method	Test Conditions	Requirement
Part I – Stress Crack Properties of Pipe			
Pipe Liner	FM 5-572, Procedure A	• 10% Igepal solution at 50°C • 600 psi applied stress • 5 replicates	Will be based on the recommendation from the NCHRP 4-26
Junction	FM 5-572, Procedure B	• 80°C water, • 250 psi applied stress • 5 replicates	4 out of 5 test specimen ≥ 1260 hr
Longitudinal Profile	FM 5-572, Procedure C	• 80°C water • applied stress see Eq. (3) and (4) in test method • 5 replicates	4 out of 5 test specimen ≥ 1260 hr
Part II – Oxidation Resistance of Pipe			
Liner and/or Crown	OIT test (ASTM D 3895)	• 200°C test temperature • 2 replicates	25 min
Liner and/or Crown	Incubation test (FM5-574) and OIT test (ASTM D 3895)	Incubation in 85°C water bath for 90 days 2 replicates of OIT test on one incubated pipe sample	Minimum OIT percent retained [target value established in December, 2003]

<u>APPENDIX J</u>

An Outline of the Full Specification
for
100-Year Service Life of High Density Polyethylene Corrugated Pipes

An Outline of the Full Materials Specification for 100-year Service Life of Corrugated High Density Polyethylene Pipes

1 Scope

1.1 This specification covers the requirements and methods of tests for corrugated polyethylene (PE) pipe, use in surface and subsurface drainage applications.

1.2 Nominal sizes of 300 to 1200 mm are included.

1.3 Materials including slow crack growth resistance, antioxidant content and depletion rate, long-term tensile strength and flexural modulus, workmanship, dimensions, pipe stiffness, and form of markings are specified.

1.4 Corrugated polyethylene pipe is intended for surface and subsurface drainage applications where soil provides support to its flexible walls. Its major use is to collect or convey drainage water by open gravity flow, as culverts, storm drains, etc.

1.5 This specification does not include requirements for bedding, backfill, or earth cover load. Successful performance of this product depends upon proper type of bedding and backfill, and care in installation. The structural design of corrugated polyethylene pipe and the proper installation procedures are given in the AASHTO's *Standard Specifications for Highway Bridges*. Upon request of the user or engineer, the manufacturer shall provide profile wall section detail required for a full engineering evaluation.

2 REFERENCED DOCUMENTS

2.1 AASHTO Standards:
- Standard Specifications for Corrugated Polyethylene Pipe: M294
- Standard Specification for Highway Bridges LRFD Bridge Design Specification

2.2 ASTM Standards*:*
- D 618, Conditioning Plastics and Electrical Insulating Materials for Testing
- D 638, Standard Test Method for Tensile Properties of Plastics
- D 883, Terms Relating to Plastics
- D4703, Standard Practice for Compression Molding Thermoplastic Materials into Test Specimens, Plaques, or Sheets
- D 2122, Determining Dimensions of Thermoplastic Pipe and Fittings
- D 2412, Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading
- D 2444, Test for Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)
- D 2990 Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

- D 3350, Standard Specification for Polyethylene Plastics Pipe and Fittings Materials
- D 3895, Standard Test Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry
- F2136 Standard Test Method for Notched Constant Ligament Stress (NCLS) Test to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe
- F 412, Terms Relating to Plastic Piping Systems

2.3 Florida Test Standard*:*

- FM 5-572, Standard Test for Determining Slow Crack Growth Resistance of HDPE Corrugated Pipes
- FM 5-573, Standard Test Method for Predicting the Crack Free Service Life of HDPE Corrugated Pipes
- FM 5-574, Standard Test Method for Predicting the Lifetime of Antioxidants and HDPE Corrugated Pipes
- FM 5-575, Standard Test Method for Determining Creep Rupture of Corrugated Pipe Liner Tensile Specimens
- FM 5-576, Standard Test Method for Predicting Long-Term Tensile Strength of HDPE Corrugated Pipes
- FM 5-577, Standard Test Method for Predicting Long-Term Flexural Modulus of HDPE Corrugated Pipes

3 TERMINOLOGY

3.1 The terminology used in this standard is in accordance with the definitions given in ASTM D 833 and ASTM F 412 unless otherwise specified

3.2 Crack – any break or split that extends through the wall

3.3 Stress-crack – an external or internal crack in a plastic caused by tensile stresses less than its short-time mechanical strength

Discussion – The development of such cracks is frequently accelerated by the environment to which the plastic is exposed. The stresses which cause cracking may be present internally or externally or may be combinations of these stresses.

3.4 Crease – An irrecoverable indentation, generally associated with wall buckling

3.5 Buckling – Any reverse curvature or deformation in the pipe wall that reduces the load-carrying capability of the pipe

3.6 Longitudinal Profiles – (Added terminology) Longitudinal profile(s) include any feature that runs along the longitudinal axis of the pipe in either continuously or repeating in regular intervals. These features may be a part of the pipe design (for example vent holes or mold line) or those resulting from extrusion defects.

3.7 Polyethylene (PE) – Plastics based on polymers made with ethylene as the primary monomer.

3.8 Reworked Material – as defined for "reworked plastic (thermoplastic)" in ASTM D 883.

3.9 Virgin Polyethylene Material – PE plastic material in the form of pellets, granules, powder, floc, or liquid that has not been subject to use or processing other than required for initial manufacture.

4 CLASSIFICATION

4.1 The corrugated polyethylene pipe covered by this specification is classified as follows:

4.1.1 Type S – This pipe shall have a full circular cross section, with an outer corrugated pipe wall and a smooth inner liner. Corrugations shall be annular.

4.1.2 Type SP – This pipe shall be Type S with perforations.

4.2 Two classes of perforations are as described in Sections 6.3.1 and 6.3.2.

5 MATERIALS

5.1 Resin Materials

5.1.1 Extruded Pipe – Pipe shall be made of virgin PE compounds which conform with the requirements of cell class 335400C as defined and described in ASTM D 3350, except that the carbon black content shall not exceed 5 percent, and the density shall not be less than 0.945 gm/cc nor greater than 0.955 gm/cc. Compounds that have higher cell classifications in one or more properties, with the exception of density, are acceptable provided product requirements are met. For slow crack growth resistance, resins shall be evaluated using the notched constant ligament stress (NCLS) test (ASTM F2136). The average failure time of the five test specimens must exceed 24 hours with no single test specimen's failure time less than 17 hours.

5.1.2 Reworked Material – In lieu of virgin PE, clean reworked material may be used by the manufacturer, provided that it meets the cell class requirements and exceptions as described in Section 6.1.1.

6 REQUIREMENTS

6.1 Workmanship – The pipe and fittings shall be free of foreign inclusions and visible defects as defined herein. The ends of the pipe shall be cut squarely and cleanly so as not to adversely affect joining or connecting.

6.1.1 Visible Defects – Cracks, creases, notches and similar extrusion defects, unpigmented or nonuniformly pigmented pipe are not permissible in the pipe or fittings as furnished.

6.1.2 For Type S pipe, the inner liner shall be fused to the outer corrugated shell at all internal corrugation crests.

6.2 Pipe Dimensions:

6.2.1 Nominal Size – The nominal size for the pipe is based on the nominal inside diameter of the pipe.

6.2.2 Wall Thickness – The inner wall of the Type S pipe shall have the following minimum thicknesses, when measured in accordance with Section 8.9.4

Diameter (in)	Wall Thickness (in)
12	0.035
15	0.040
18	0.051
21	0.059
24	0.059
27	0.059
30	0.059
35	0.067
41	0.07
47	0.07

6.2.3 Inside Diameter Tolerances – The tolerance on the specified inside diameter shall be 4.5 percent oversize and 1.5 percent undersize, but not more than 1.12 in oversize when measured in accordance with Section 8.9.1

6.2.4 Length – Corrugated PE pipe may be sold in any length agreeable to the user. Lengths shall not be less than 99 percent of the stated quantity when measured in accordance with Section 8.9.2.

6.3 Perforations – When perforated pipe is specified, the perforations shall conform to the requirements of Class 2, unless otherwise specified in the order. Class 1 perforations are for pipe intended to be used for subsurface drainage or combination storm and underdrain. Class 2 perforations are for pipe intended to be used for subsurface drainage only. The perforations shall be cleanly cut so as not to restrict the inflow of water. Pipe connected by couplings or bands may be non-perforated within 4 inches of each end of each length of pipe. Pipe connected by bell and spigot joints may not be perforated in the area of the bells and spigots.

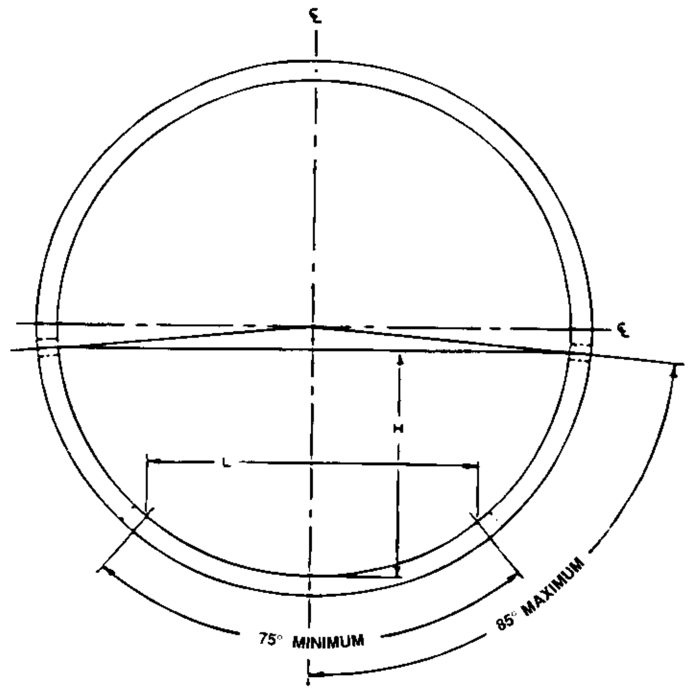

Figure 1—Requirements for Perforations

Table 1—Rows of Perforations, Height "H" of the Centerline of the Uppermost Rows above the Invert, and Chord Length "L" of Unperforated Segment, for Class 1 Perforations

Nominal Diameter (in)	Rows of Perforations[A]	H Maximum[B] (in)	L Minimum[B] (in)
12	6	5.4	7.6
15	6	7.2	10
18	6	8.1	11.3
21	6	9.1	12.6
24	8	([c])	([c])

[A] Minimum number of rows. A greater number of rows for increased inlet area shall be subject to agreement between purchaser and manufacturer.
Note: The number of perforations per inch in each row (and inlet area) is dependent on the corrugation pitch.
[B] See Figure 1 for location of dimensions "H" and "L"
[C] H (max.) = 0.46D; L (min.) = 0.64, where D = nominal diameter of pipe (in)

6.3.1 Class 1 Perforations — The perforations shall be approximately circular and shall have nominal diameters of not less than 0.2 in nor greater than 0.4 in and shall be arranged in rows parallel to the axis of the pipe. The perforations shall be located in the external valleys with perforations in each row for each corrugation. The rows of perforations shall be arranged in two equal groups placed symmetrically on either side of the lower unperforated segment corresponding to the flow line of the pipe. The spacing of the rows shall be uniform. The distance between the center lines of the rows shall not be less than 1 in. The minimum number of longitudinal rows of perforations, the maximum height of the center lines of the uppermost rows of perforations above the bottom of the invert, and the inside chord lengths of the unperforated segments illustrated in Figure 1 shall be as specified in Table 1.

6.3.2 Class 2 Perforations — Circular perforations shall be a minimum of 0.2 in and shall not exceed 0.4 in. in diameter. The width of slots shall not exceed 0.12 in. The length of slots shall not exceed 2.8 in for 12 in and 15 in pipe and 3 in for 18 in and larger pipe. Perforations shall be placed in the external valleys and uniformly spaced along the length and circumference of the pipe. The water inlet area shall be a minimum of 30 cm^2/m for pipe sizes 12 to 18 in and 40 cm^2/m for pipe sizes larger than 18 in. All measurements shall be made in accordance with Section 8.9.3.

6.4 Pipe Stiffness – The pipe shall have a minimum pipe stiffness at 5 percent deflection as follows when tested in accordance with Section 8.1.

Diameter (in)	Pipe Stiffness (psi)
12	50
15	42
18	40
21	38
24	34
27	30
30	28
35	22
41	20
47	18

6.5 Pipe Flattening — There shall be no evidence of wall buckling, cracking, splitting, or delaminating, when the pipe is tested in accordance with Section 8.2.

6.6 Brittleness — Pipe specimens shall not crack or split when tested in accordance with Section 8.3. Five non-failures out of six impacts will be acceptable.

6.7 Environmental Stress Cracking — The pipe shall be test according to Section 8.4.

6.8 Oxidation Resistance – The pipe shall be test according to Section 8.5

6.9 Long-term Tensile Strength – The 100-year tensile strength shall be determined according to Section 8.6.

6.10 Long-term Flexural Modulus – The 100-year tensile strength shall be determined according to Section 8.7.

6.11 Fitting Requirements*:*

6.11.1 The fittings shall not reduce or impair the overall integrity or function of the pipe line.

6.11.2 Common corrugated fittings include in-line joint fittings, such as couplings and reducers, and branch or complimentary assembly fittings such as tees, wyes, and end caps. These fittings are installed by various methods.

Note 1 — Only fittings supplied or recommended by the pipe manufacturer should be used. Fabricated fittings made from pipe meeting the requirements of the pipe specification should be acceptable providing that the joints are adequately lapped or reinforced. Soil tightness is a function of opening size, channel length, and backfill particle size. A backfill material containing a high percentage of fine-graded soils requires investigation for the specific type of joint to be used to guard against soil infiltration. Information regarding joint soil tightness criteria can be found in AASHTO's *Standard Specifications for Highway Bridges*, Division II, Section 26, "Metal Culverts."

6.11.3 All fittings shall be within an overall length dimensional tolerance ±0.5 in of the manufacturer's specified dimensions when measured in accordance with Section 8.9.2.

6.11.4 Fittings shall not reduce the inside diameter of the pipe being joined by more than 0.5 in. Reducer fittings shall not reduce the cross-sectional area of the small size.

6.11.5 Couplings shall be corrugated to match the pipe corrugations and shall provide sufficient longitudinal strength to preserve pipe alignment and prevent separation at the joints. Couplings shall be bell and spigot, split collar, or screw-on collar. Split couplings shall engage at least two full corrugations on each pipe section.

6.11.6 Pipe connections shall not separate to create a gap exceeding 0.2 in when measured in a radial direction between pipe and coupling, or between bell and spigot portions of pipe, when tested according to Section 8.8.1. Fittings shall not crack or delaminate.

6.11.7 The design of the fittings shall be such that when connected with the pipe, the axis of the assembly will be level and true when tested in accordance with Section 8.8.2.

6.11.8 Other types of coupling bands or fastening devices which are equally effective as those described, and which comply with the joint performance criteria of AASHTO's *Standard Specifications for Highway Bridges*, Division II, Section 26, may be used when approved by the purchaser.

7 CONDITIONING

7.1 Conditioning – Condition the specimen prior to test at 21 to 25°C for not less than 40 hours in accordance with Procedure A in ASTM D 618 for those tests where conditioning is required, and unless otherwise specified

7.2 Conditions — Conduct all tests at a laboratory temperature of 21 to 25°C unless otherwise specified herein.

8 TEST METHODS

8.1 Pipe Stiffness - Select a minimum of three (3) pipe specimens and test for pipe stiffness (PS), as described in ASTM D 2412 except for the following: (1) the test specimens shall be a minimum of one diameter length; (2) locate the first specimen in the loading machine with an imaginary line connecting the two seams formed by the corrugation mold (end view) parallel to the loading plates, when applicable. The specimen must lie flat on the plate within 3 mm and may be straightened by hand bending at room temperature to accomplish this. Use the first location as a reference point for rotation and testing of the other two specimens. Rotate subsequent specimens 45 and 90 degrees, respectively, from the original orientation. Test each specimen in one position only; (3) the deflection indicator shall be readable and accurate to ±0.0008 in; (4) the residual curvature found in tubing frequently results in an erratic initial load/deflection curve. When this occurs, the beginning point for deflection measurement shall be at a load of 4.5 ± 1 lb. The point shall be considered as the origin of the load deflection curve.

Note 2—The parallel plates must exceed the length of the test specimen as specified above.

8.2 Pipe Flattening — Flatten the three-pipe specimens from Section 8.1 until the vertical inside diameter is reduced by 20 percent. The rate of loading shall be the same as in Section 8.1. Examine the specimen with the unaided eye for cracking, splitting, or delamination. Wall buckling is indicated by reverse curvature in the pipe wall accompanied by a decrease in load carrying-ability of the pipe.

8.3 Brittleness — Test pipe specimens in accordance with ASTM D 2444 except six specimens shall be tested, or six impacts shall be made on one specimen. In the latter case, successive impacts shall be separated by 120 ± 10 degrees for impacts made on one circle, or at least 12 in longitudinally for impacts made on one element. Impact points shall be at least 6 in from the end of the specimen. Tup B shall be used, with a mass of 1 lb. The height of drop shall be 10 ft. Use a flat plate specimen holder. Condition the specimens for 24 hours at a temperature of 14 ± 2ºC, and conduct all tests within 60 seconds of removal from this atmosphere. The center of the falling tup shall strike on a corrugation crown for all impacts.

8.4 Environmental Stress Crack — Test different parts of the pipe for environmental stress cracking in accordance with FM 5-572 and FM 5-573. The summary of tests is shown in Table 2-Part I.

8.4.1 Pipe Liner – The evaluation of pipe liner shall be according to FM 5-572, procedure A. Five specimens shall be tested and the average failure time shall be based on the recommendation from the NCHRP 4-26

8.4.2 Pipe Junction – The test procedure shall be according to FM 5-572, Procedure B and FM 5-573. The failure time at 500 psi applied load at 20^{o}C shall exceed 100 year.

8.4.3 Pipe Longitudinal Profile – The test procedure shall be according to FM 5-572, Procedure C and FM 5-573. The failure time at 500 psi applied load at 20°C shall exceed 100 year.

8.5 Oxidation Resistance – Test pipes for their antioxidant contents and depletion rates to determine lifetime of antioxidant and corrugated pipe

8.5.1 Antioxidant Content – Determine the amount of antioxidants in the pipe using oxidative induction time (OIT) according to ASTM D 3895 and FM 5-574. The initial OIT of pipe is tentatively defined at 25 min. as indicated in the interim specification. The value shall be changed based on results of the long-term oxidative resistance test of the pipe.

8.5.2 Antioxidant Lifetime – Determine the lifetime of antioxidants in the pipe using OIT test and elevated temperature incubation according to procedures described in FM 5-574, as defined in Table 2-Part II.

8.5.3 Lifetime of Pipe – The thermal oxidation degradation of pipe shall be determined according to FM 5-574, as defined in Table 2-Part II. The lifetime of a pipe is defined at 80% decrease in breaking strain and shall exceed 100 year.

8.6 Long-term Tensile Strength – The 100 year tensile strength of pipe shall be determined according to FM 5-575 and FM 5-576. The tests shall be performed on pipe liner at three elevated temperatures at 65, 75 and 85°C. The test conditions are defined in Table 2-Part III.

8.7 Long-term Flexural Modulus – The 100 year flexural modulus of pipe shall be determined according to FM 5-577. The stress relaxation test shall be carried out based on parallel plate test (ASTM D 2412). The test is limited to pipe diameter of 24 inches. The test conditions are defined in Table 2-Part IV.

8.8 Joints and Fittings

8.8.1 Joint Integrity — Assemble each fitting or coupling to the appropriate pipe in accordance with the manufacturer's recommendations. Use pipe samples at least 300 mm in length. Assemble a specimen at least 600 mm in length with the connection at the center. Load the connected pipe and fitting between parallel plates at the rate of 0.5 in per minute until the vertical inside diameter is reduced by at least 20 percent of the nominal diameter of the pipe. Inspect for damage while at the specified deflection and after load removal. Measure the maximum radial distance between pipe and fittings, or between bell and spigot, during test and after load removal.

8.8.2 Alignment — Assure that the assembly or joint is correct and complete. If the pipe is bent, it should be straightened prior to performing this test. Lay the assembly or joint on a flat surface and verify that it will accommodate straight-line flow.

8.9 Dimensions

8.9.1 Inside Diameter — Measure the inside diameter of the pipe with a tapered plug in accordance with ASTM D 2122. As an alternative, measure the inside diameter with a suitable device accurate to ±0.12 in on two sections. Take eight measurements equally spaced around the circumference of each section and average these 16 measurements. The average inside diameter shall meet the requirements of Section 6.2.3.

8.9.2 Length — Measure pipe with any suitable device accurate to ±0.24 in. in 10 ft. Make all measurements on the pipe while it is stress-free and at rest on a flat surface in a straight line.

8.9.3 Perforations — Measure dimensions of perforations on a straight specimen with no external forces applied. Make linear measurements with instruments accurate to 0.008 in.

8.9.4 Wall Thickness — Measure the wall thickness in accordance with ASTM D 2122.

9 INSPECTION AND RETEST

9.1 Inspection – Inspection of the material shall be made as agreed upon by the purchaser and the seller as part of the purchase contract.

9.2 Retest and Rejection — If any failure to conform to these specifications occurs, the pipe or fittings may be retested to establish conformity in accordance with agreement between the purchaser and seller. Individual results, not averages, constitute failure.

10 MARKING

10.1 All pipe shall be clearly marked at intervals of no more than 12 ft as follows:

10.1.1 Manufacturer’s name or trademark,

10.1.2 Nominal size,

10.1.3 This specification designation, FL-DOT Specification XX,

10.1.4 The plant designation code, and

10.1.5 The date of manufacture or an appropriate code.

10.1.6 Fittings shall be marked with the designation number of this specification, FL-DOT Specification XX, and with the manufacturer’s identification symbol.

11 QUALITY ASSURANCE

11.1 A manufacturer’s certificate that the product was manufactured, tested, and supplied in accordance with this specification, together with a report of the test results, and the date each test was completed, shall be furnished upon request. Each certification so furnished shall be signed by a person authorized by the manufacturer.

Table 2 – Specification for 100-year Design Life of Corrugated HDPE Pipe

Pipe Location	Test Method	Test Conditions	Requirement
Part I – Stress Crack Properties of Pipe			
Pipe Liner	FM 5-572, Procedure A	• 10% Igepal solution at 50°C • Applied stress at 600 psi • 5 replicates	Will be based on the recommendation from the NCHRP 4-26 project
Junction	FM 5-572, Procedure B FM 5-573	• 60, 70 and 80°C water, • Applied stress see Table 1 • Minimum of 3 stress levels • 5 replicates per stress level	• Generate a brittle master curve at 20°C • Determine the failure time at 500 psi shall exceed 100 yr
Longitudinal Profile	FM 5-572, Procedure C FM 5-573	• 60, 70 and 80°C water • Applied stress see Eq. (3) and (4) • 5 replicates	• Generate a brittle master curve at 20°C • Determine the failure time at 500 psi shall exceed 100 yr
Part II – Oxidation Resistance of Pipe			
Liner and/or Crown	ASTM D 3895	• 200°C test temperature • 2 replicates	Will be specified based on lifetime prediction results
Liner and/or Crown	Incubation test (FM 5-574) and OIT test (ASTM D 3895) Tensile test (ASTM D638)	• Incubation in water baths at 65, 75 and 85°C • Retrieve incubated sample every 3-month and perform • OIT test on the liner • tensile test on the liner	• Predict lifetime of antioxidant at 20°C • Predict lifetime of pipe liner at 20°C based on 20% break elongation retained
Part III – Long-Term Tensile Strength			
Liner	FM 5-575 and FM 5-576	• Creep rupture test in water at 65, 75 and 85°C • Applied stress see Table 1 • Generate brittle curve at each test temperature	• Shift elevated temperature data to 20°C • Determine tensile strength at 100 year
Part IV – Long-Term Flexural Modulus			
Pipe	FM 5-577	• Stress relaxation test in air from 35 to 85°C • Obtain the modulus versus time curve at each temperature	• Shift elevated temperature data to 20°C • Determine modulus value at 100 year